An investigation of the life history of the gorse pod moth (*Cydia succedana*) and its effectiveness at reducing gorse (*Ulex europaeus*) seed production

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by

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Lincoln University

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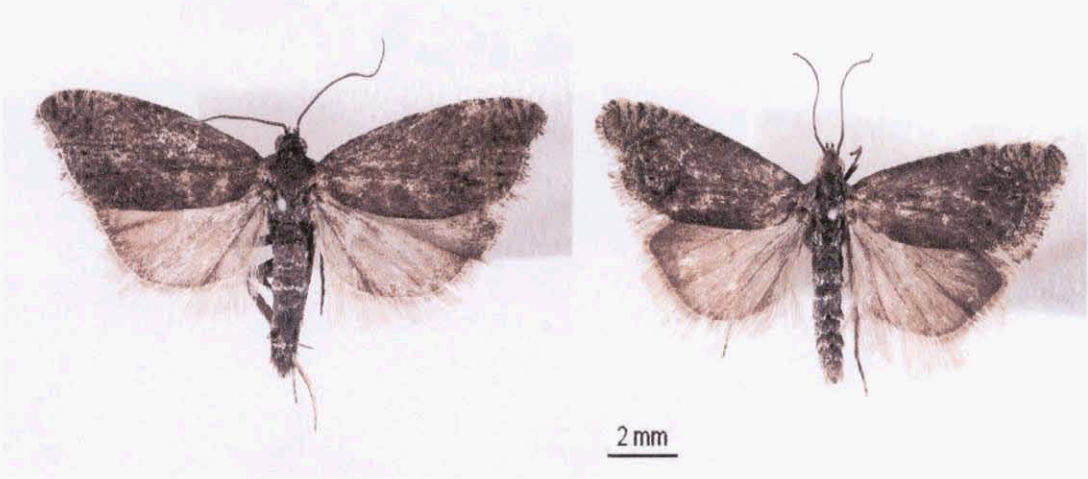

Cydia succedana (Denis & Schiffermüller) moths, male (left) and female (right).

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Gorse (*Ulex europaeus* L.) has been a major weed in New Zealand and other temperate countries throughout the world for over 100 years. In 1931, *Exapion ulicis* (Förster) (gorse seed weevil) was introduced to New Zealand in an attempt to control the spread of gorse. However, gorse in much of New Zealand has two reproductive cycles per year and *E. ulicis* is active only in spring. In 1992, *Cydia succedana* (gorse pod moth), which has two generations per year, was introduced into New Zealand to improve the biological control of gorse.

Moths were collected from McLeans Island, Canterbury, and placed under laboratory conditions for egg and larval development experiments. Lower temperature threshold for egg and larval development of *C. succedana* was 11.5°C, which is similar to other species in the same genus.

The limited results obtained indicated that *C. succedana* has six larval instars, again similar to other insects of the same genus. *Cydia succedana* larvae damaged up to three gorse pods.

Moth phenology was studied at only two of the sites. At these sites, McLeans Island and Hinewai Reserve, the phenology of *C. succedana* was synchronised with the phenology of gorse, especially for the first flowering. However, there was less synchronicity for the second flowering. *Cydia succedana* was more active at the warmer site of McLeans Island had a larger population of *C. succedana* male moths. In addition, *C. succedana* was active for longer and became active earlier there.

Seven field sites were chosen in the South Island of New Zealand, with different altitudes and climatic conditions. Monthly inspections were made of the reproductive stage of the gorse and gorse pods were sampled when ripe.

Gorse at Golden Bay sites produced mature seeds throughout the study period. Sites further south had much shorter reproductive seasons with only one gorse reproductive season per year as confirmed by gorse seed collected in seed trays.

There was a wide variation in the number of seeds in the seed trays, 0 – 304 seeds/m^2. This represented a big reduction in the number of gorse seeds compared with previous reports. Viability of the seed from the seed trays and sample pods was tested. Seed from the seed trays had a viability of 60% whereas seed from sampled pods had a viability of 80%.

The effectiveness of both seed feeding insects at reducing the amount of viable gorse seed produced varied from site to site, with gorse seed weevil being more effective at the southern sites. At the northern sites the gorse pod moth was more effective. However, the gorse bushes still produced a significant amount of seed at all sites.

The results indicate that further gorse seed feeding biological agents could be required to assist in the biological control of gorse, especially in southern regions where *C. succedana* does not appear to be as successful. The implications of these results are briefly discussed.

Keywords: Gorse (*Ulex europaeus*), gorse pod moth (*Cydia succedana*), gorse seed weevil (*Exapion ulicis*), seed viability, threshold temperature, larval development, egg development, instars, phenology.

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Chapter 1

General Introduction

1.1 Gorse release and subsequent problems

Gorse (*Ulex europaeus* L.) was introduced into New Zealand before 1835 as an inexpensive, quick growing hedge for stock containment and shelter (Moss, 1960). However, due to the lack of biological predators and the favourable climate over much of New Zealand, in a short space of time there was a multiplication of the number of gorse plants, as well as many seed stored below the soil surface. As a result, in 1900 gorse was declared a noxious weed (Moss, 1960).

Gorse has considerable value despite having a noxious weed status. It provides pollen for bees, which provides significant income for beekeepers. Gorse also provides fodder for sheep and goats; in fact, goats will eat gorse in preference to grasses and clovers. Gorse stabilises eroding land and also allows regeneration of native forest plants in some areas, e.g., Banks Peninsula. In some areas of New Zealand, especially Canterbury, gorse is still used as hedge material (Hill, 1987) but as the dairy farming practices extend, the number of gorse hedges is becoming fewer.

Gorse is regarded as a major weed in agriculture and forestry. It is a particular problem in low fertility hill country soils where it can compete effectively with newly planted trees and sown pasture (MacCarter and Gaynor, 1980). In addition, hill country farmers faced extreme financial stress; therefore chemical control of gorse was not economic. Furthermore, today's farmers face public opposition to using chemicals to control gorse. This opposition has seen many chemicals banned, including 2,4,5-T, which was once heavily used. This chemical was effective at killing existing gorse plants, providing that every branch and twig was wet with the chemical. However, it was ineffective against the hard gorse seed underground, which can survive for many years. As a consequence of the pressure from the public and the ineffectiveness at making seed lose the viability, the amount of research into developing new chemicals has reduced. The emphasis in recent years is on research into biological control of various weeds, including gorse. Farmers are now encouraged to use alternative methods for gorse control such as release of biological agents. This is because the release of biological agents allows a reduction in the use

of herbicides. This also brings about less physical work, as well as less use of fossil fuels etc.

A good biological agent is one that keeps the weed growth under control, i.e. the area that the weed is infested does not increase, or the weed area becomes smaller. Another important factor for good biological agents is the fact that they do not transfer to non-target plants.

There are 94 phytophagous species that are known to attack gorse species in Europe. Of these, there are only 16 that are sufficiently host-specific to be considered as biological control agents in New Zealand. However, none of the species that attack the roots or stems was considered sufficiently host specific to release in New Zealand. Research in New Zealand has concentrated on the eight species that attack the seeds or green foliage (Hill, 1983; Hill, 1987). This study will examine the effectiveness of one of those agents, *Cydia succedana* (Denis & Schiffermüller) (Lepidoptera: Tortricidae), under different climatic conditions and at different altitudes.

1.2 Biology of *Cydia succedana*

1.2.1 Life Cycle

Cydia succedana lays its eggs on *Ulex, Genista, Sarothamnus* or *Lotus* plants in Europe (Emmet, 1988). In New Zealand, *Cydia succedana* completes both generations in the pods of *Ulex europaeus* (Hill, 1990). The larvae feed on unripe seeds in the pods and move from pod to pod from June in the first generation and September – April in the second generation in Europe (Emmet, 1988). In New Zealand, *Cydia succedana* larvae are active from September to June, depending on the climatic conditions. The second generation over winters fully-fed from October (in Europe) in a cocoon spun in leaf-litter or the soil and pupates in the cocoon. Larvae pupate in April and June – July in Europe (Emmet, 1988).

Male, sexually mature adults fly actively in sunshine, whereas females fly towards sunset. Both sexes are occasionally attracted to light (Emmet, 1988). The insect is bivoltine in the south of the British Isles and is univoltine in Scotland (Bradley *et al.* 1979). A similar trend has occurred in New Zealand where the

biological agent is univoltine in the cooler, southern regions, e.g. Mackenzie Basin and bivoltine further north, e.g. Golden Bay.

1.2.2 Taxonomy

According to Bradley *et al.* (1979) *Cydia succedana* is found in the United Kingdom. However, recent work by Razowski (2002) agreed with an earlier separation made by Danilevsky & Kuznetzov (1968), which split this species in two: *C. succedana* and *C. ulicetana* Haworth. Of these, only *C. ulicetana* occurs in the United Kingdom (D. Agassiz pers comm). In Portugal, where New Zealand moths were also sourced, a number of closely related species are present, including *C. ulicetana*, *C. vallesiaca* (Sauter), *C. intexta* (Kuznetsov) and *C. conjunctana* (Mann) (J. Baixeras, pers. comm.).

Cydia succedana has a thorn-like protuberance on the genitalia that *C. ulicetana* lacks (Danilevsky & Kuznetzov, 1968). Moths with genitalia resembling both forms are present in New Zealand, but only one form has been reared from non-target plants. New Zealand tests have reared what appears to be *C. ulicetana* from *Genista monspessulana* (L.) Johnson, *Lupinus arboreus* L., *Cytisus scoparius* L. and *Lotus pedunculatus* Cav as well as gorse. Since *C. ulicetana* is now regarded as the only species in the United Kingdom and the non-target records in New Zealand suggest this species is 'misbehaving', it may be that there was a problem with the host-range testing (only the United Kingdom population was tested extensively, then mixed with Portuguese moths, before release). It is also possible *C. ulicetana* was also introduced from Portugal, and the Portuguese population was less host-specific than the United Kingdom population.

1.3 Impact and release of *Cydia succedana* in New Zealand

1.3.1 Impact Report

A shipment of *Cydia succedana* was imported into New Zealand on 4 August 1989 and was kept under quarantine to evaluate its potential as a biological agent for gorse, as well as ensuring that it was parasite, predator and disease free. *Cydia succedana* was reared for several generations to evaluate its potential as a biocontrol agent for gorse. The impact evaluation was undertaken using the internationally

accepted protocols devised by Wapshere (1975). As a result of the impact report, release of *C. succedana* in New Zealand was granted in 1992.

1.3.2 Sites of release

The first release site was at Darfield, Canterbury, and the moth has now been released throughout New Zealand. Since 1992, *C. succedana* has been released in 134 sites throughout New Zealand. It has become established at 78% of the sites that have been adequately assessed (Figure 1.1). There appears to be no geographic establishment pattern and it seems to establish wherever gorse appears (Hill and Gourlay, 2002). For an agent to be judged as established, it is required to survive one season and produce at least one generation (A. H. Gourlay, pers. comm.). There have been further releases that are not shown in Figure 1.1. For example, in Golden Bay where there was a release in 1993 and it is now well established throughout the district (M. Doyle, pers. obs.).

1.4 Research into effectiveness and life history of *Cydia succedana*

1.4.1 Location of sites

The experimental sites for this work were located throughout the South Island of New Zealand. The furthest north were situated within Golden Bay, Nelson: Bainham (40° 47.42' S 172° 32.35' E, 90 m above sea level), Onekaka (40° 46.32' S 172° 43.49' E, 63 m above sea level) and at East Takaka (40° 54.45' S 172° 50.18' E, 50 m above sea level). There was one site adjacent to Christchurch Airport, McLeans Island (43° 28.00' S 172° 28.99' E, 65 m above sea level) and one east of Christchurch, Hinewai Reserve (E 43° 48.61' S 173° 01.67' E, 470 m above sea level), close to the township of Akaroa. One site was in the Mackenzie Basin, at Lake Ohau (44° 10.24' S 169° 49.26' E, 556 m above sea level), and the last site was south of Oamaru at Trotters Gorge (45° 24.27' S 170° 47.05' E, 53 m above sea level). The locations are shown in Figure 1.2. The latitude, longitude and altitude of each individual sampled gorse bush are given in Appendix 1.

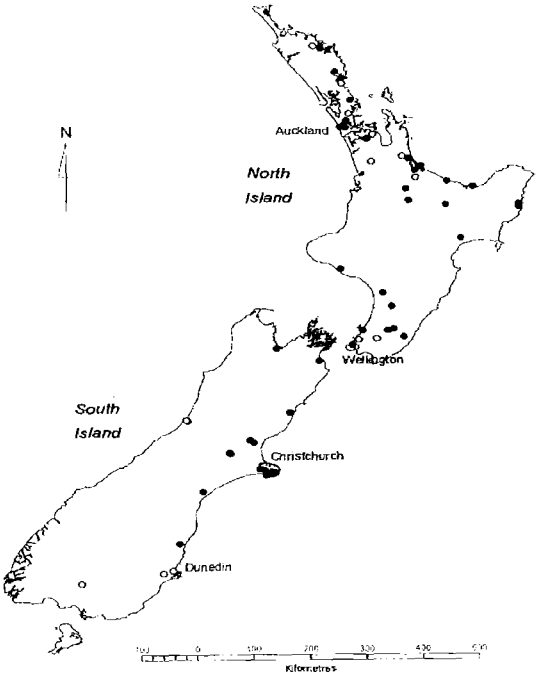


Figure 1.1: Sites in New Zealand where *Cydia succedana* has been released (o) and where establishment has been confirmed (•) (Hill and Gourlay, 2002)

1.4.2 Soil conditions and types

The soil types at the experimental sites were different, and may have contained different amounts of nutrients necessary for gorse growth, although gorse manages to grow successfully almost anywhere in New Zealand.

The Bainham soil types are Otere and Denniston soils, which are lowland yellow-brown earths, and upland and high country podzolised yellow-brown earths and podzols respectively (Anon., 1967). These soils have weaker weathering and, therefore, lower production and less turnover of organic matter. Gley podzols with a thin iron pan are formed under a wide range of vegetation (Anon., 1967). The main profile features of these soils are dark grey, silt loam topsoils with crumb to nutty structures and a turfy top when formed under grass; the lower part of the topsoil is a grey to pale grey nutty structured silt loam that sometimes has bluish-grey mottles. There is a sharp boundary to a thin wavy iron pan blackish above and rusty brown below; the subsoil is yellowish-brown friable blocky structured silt loam, merging to rock (Anon., 1967).

Soil types in the Onekaka region are Ikamatua and Onahau. These soils are lowland yellow-brown earths, and lowland podzolised yellow-brown earths and

podzols (Anon., 1967). The principal characteristics of these soils are shallow greyish-brown to dark greyish-brown silt loam to loam topsoils with granular or crumb structure; yellowish-brown to brownish-yellow friable to firm or very firm silt loam subsoils, sometimes mottled grey or with thin iron pans, and with moderately developed blocky structure. Clay and iron alluvial horizons are common, and mottling due to wetness is prominent (Anon., 1967).

East Takaka soils are Pikikiruna, which are rendzina and related soils (Anon., 1967). These soils' topsoil has a very dark brown loam that is very friable. The soil has a strongly developed fine and medium crumb and cast granular structure with an indistinct boundary. The subsoil is a dark brown loam that is very friable with a moderately developed medium nutty and fine crumb structure. These soils are high in nutrients, however, when cleared for pasture, they respond well to topdressing with phosphate fertiliser (Anon., 1967).

There are also Brooklyn soils present at East Takaka, which are brown granular loams and clays (Anon., 1967). These soils contain some montmorillonite as well as oxide clays. These soils are high in phosphorus and other nutrients but the sulphur levels are low. They are dark brown to very dark brown silt loams to heavy silt loams with very friable well developed granular structure, or in places crumb and granular structure, merging into dark brown or dark yellowish brown silt loam with very friable well developed granular to nutty structure (Anon., 1967).

The soils at the McLeans Island site are Selwyn, which are very stony sands and the soil type is recent (Cox and Mead, 1971). The principal profile features of recent soils are dark greyish brown to dark brown topsoils of varying textures, friable with weakly developed granular to crumb structures, merging gradually into olive to olive-brown subsoils with very weakly developed blocky structures (Cutler, 1968).

Hinewai Reserve has Stewart-Summit soils, which are brown granular loams and clays (Anon., 1967). These soils are brown soils with high structural stability with relatively high iron and aluminium oxide content. The soils are leached and weathered. Oxide clays and vermiculite are dominant clay minerals and the phosphorus levels may be low (Anon., 1967). The soil's profile features are dark brown to very dark brown silt loams to heavy silt loams with very friable well-developed structure, or crumb and granular structure, merging into dark-brown or dark yellowish-brown silt loam with very friable well developed granular to nutty structure (Anon., 1967).

The site at Lake Ohau has Cass and Kaikoura soils that are upland and high country yellow-brown earths (Anon., 1967). Principal profile features of the yellow-brown earths are greyish-brown to dark greyish-brown topsoils that are loose to very friable in fine sandy loams and friable to very friable when the textures are silt loams. Subsoils are brownish-yellow to pale yellow and yellowish- brown sandy loams and silt loams, friable to very friable, with weakly developed crumb and blocky structure (Cutler, 1968).

Trotters Gorge has Waimahaka – Taratu soils, which are lowland yellow-brown earths (Anon., 1967). Principal profile features are greyish-brown to dark greyish-brown silt loam topsoils, friable with nutty or nutty and crumb structure; yellowish-brown to brownish-yellow silt loam to heavy silt loam subsoils which are friable to firm with nutty or fine blocky structure. Soil moisture is normally at or near field capacity and it is uncommon for these soils to dry out (Anon., 1967).

1.4.3 Climatic records

Climate, especially temperature, is likely to affect the phenology of both the gorse plants and the moth. For that reason, the sites chosen for this study were expected to have different climatic conditions. Historic data show that there is a difference of rainfall at the sites (Table 1.1). Appendices 2 and 3 show the daily rainfall and daily maximum and minimum temperatures.

1.4.4 Aim of study

The purpose of this study was to investigate aspects of the biology of *C. succedana*. The overall purpose was to ascertain the percentage of gorse seed production that was damaged by the gorse seed feeding insects, *C. succedana* and *Exapion ulicis*. The specific objectives concerned were to ascertain whether climatic conditions had an effect on the phenology and effectiveness of *Cydia succedana* and were to:

1. Ascertain the phenology of the moth under different climatic conditions.
2. Determine the threshold temperature for egg and larval development of *C. succedana*.
3. Investigate the infestation of gorse pods by *C. succedana* and *Exapion ulicis* and ascertain the number of seed pods attacked by *C. succedana*.

4. Assess the percentage of viable gorse seed that falls to the ground, as well as the percentage of sampled seed pods that contained viable seed.

Table 1.1. Average yearly of rainfall at the different sites of the gorse studies

Site	Rainfall (mm)
Bainham	3,830
Onekaka	2,307
Takaka	2,167
East Takaka	2,000
Hinewai	1,650
Oamaru	558
Palmerston	634
Chain Hills	445

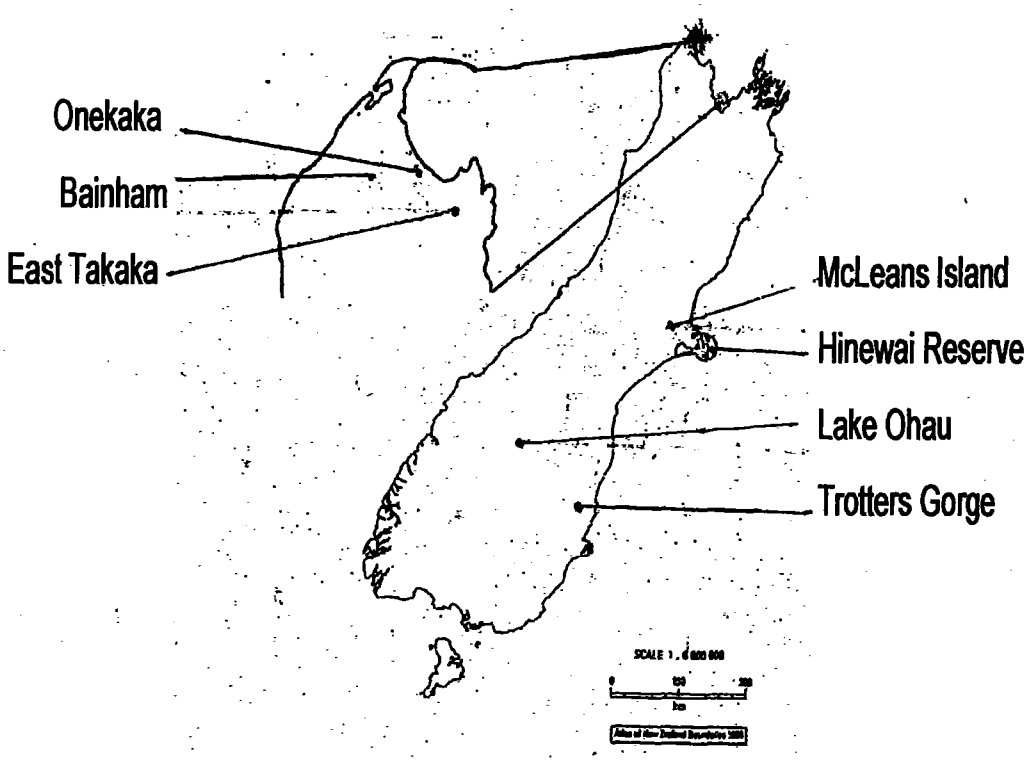


Figure 1.2: Map of South Island, New Zealand showing the locations of each sample site.

Chapter 2

Literature Review

2.1 Biology of Gorse

2.1.1 Physical attributes of gorse

Gorse (*Ulex europaeus*) belongs to the family Faboideae Gorse is in the genus *Ulex*. There are two other European species in the genus, *U. minor* Roth. and *U. galli* Planchon that are distinguished from *U. europaeus* on the basis of smaller flowers and pods, but these two species are not present in New Zealand. '*Ulex europaeus* is generally a hexaploid but diploids and tetraploids also occur'(Misset and Gourret, 1996).

Gorse is a perennial evergreen shrub that grows in excess of 3 m high with a crown diameter of up to 4 m in British Columbia (Clements *et al.*, 2001). In New Zealand, gorse grows profusely in many areas and a mean canopy height of 4 m has been recorded, with a maximum height of 7 m (Lee *et al.*, 1986). Plants are armed with conspicuous spines (Clements *et al.*, 2001).

2.1.2 Morphology of gorse

'The majority of the gorse root systems can be found in the top 10 cm of soil. However, in some soils, the taproot can penetrate to 30 cm below the soil surface'(Grubb *et al.*, 1969). 'Gorse is a member of a genus of woody legumes with aerobic nitrogen-fixing bacteria contained in long-lived root nodules'(Reid, 1973).

2.1.3 Phenology of gorse

'Seedlings produce trifoliate leaves. In the next growth stage, spines (prickly leaves) replace the trifoliate leaves and smaller, acicular leaves are also produced'(Bienick and Millington, 1968).

Gorse plants require about 18 months of growth and development before they flower (Parsons, pers. comm.). In cooler climates, e.g., the Mackenzie Basin of New Zealand, and in northern Europe, flowering occurs only once a year, in the spring

(Hill *et al.*, 1991a). However, where there is a favourable climate, such as in Golden Bay, New Zealand, there is often a second flowering (Cowley, 1983).

'Flowering commences in the second or third growth season in British Columbia'(Zielke *et al.*, 1992). It is assumed that gorse in New Zealand will follow a similar flowering pattern but it may vary according to climatic conditions. Gorse flower buds are only on the current season's new growth, after it has hardened. Flower buds are found at the tip, but not on the main stem of the branch. 'Buds remain inactive for several months after forming; they begin to swell approximately one month before they open'(Markin and Yoshioka, 1996).

The flower is pea-like, approximately 2 cm long and bright yellow with a distinct keel containing the stamens and stigma. A single branch 50 cm long can produce 500 - 1000 flowers over a two to three month flowering period. 'If an individual flower is not pollinated, it aborts in three to four days'(Markin and Yoshioka, 1996).

Flowers are not self-pollinating and require an insect to probe the keel base for nectar. This trips the mechanism that opens the keel and releases the stamens and stigma. On release, these parts spring up and strike the insect on its ventral surface, depositing new pollen and removing foreign pollen (Markin and Yoshioka, 1996).

Gorse is mainly spread by seed dispersal. In most of Europe, there is only one seeding period per year, but in much of New Zealand there are two. The first is from November to January, followed by a lighter winter seeding from June to August. 'The seed develops a hard, water impermeable testa that prevents immediate germination'(MacCarter and Gaynor, 1980) and enables it to 'remain viable in the soil for 25 to 40 years'(Zabiewicz, 1976) although there have been reports of gorse seed remaining viable for up to 75 years (W.J. Davis, pers. comm.). 'Organic inhibitors leached from older plants may also prevent germination'(Zabicwicz, 1976); 'fewer seeds germinate and the seedling death rate is higher under old plants than in the open'(Ivens, 1978). 'Gorse seedlings may colonise areas of grasslands if the grazing pressure is insufficient to defoliate the seedlings before their spines become well developed and hardened'(MacCarter and Gaynor, 1980).

2.2 Significance of Gorse in New Zealand

The need to control gorse requires a balanced approach between competing interests. These competing interests include its impact on agricultural and forestry production, against food for bees and goats. There are also beneficial environmental effects such as hedges and nurse plants for the regeneration of native forest as well as nitrogen fixation, which assists native vegetation establishment. 'Also to be considered when making decisions on gorse control are the community's attitudes to different methods of control'(Hill, 1987).

2.2.1 Gorse growth

In pastures, particularly in areas of low fertility, gorse is more competitive than grasses and, if left unattended, will form dense thickets that are impenetrable to livestock. 'Gorse can survive in low fertility areas due to its nitrogen fixing ability'(MacCarter and Gaynor, 1980). 'It is capable of fixing up to 200 kg N ha^{-1} yr^{-1}'(Egunjobi, 1969). If gorse is controlled in an area that is later abandoned, the area will revert to gorse. As a result, there is a constant need to manage gorse. There are thousands of hectares of New Zealand pastureland that are affected by gorse and there are many hard gorse seeds lying below the soil surface that only require to be disturbed to germinate (W.J. Davis, pers. comm.).

2.2.2 Agriculture

Though many of gorse's effects on agriculture are undesirable, there are also some beneficial aspects of gorse, which are discussed below.

2.2.2.1 Beekeeping

In spring and autumn, gorse pollen is an important source of pollen for honey bees (*Apis mellifera* L.) throughout New Zealand. However, as biological control will not completely destroy this weed, this pollen source would not be totally removed. 'If substantial gorse control were possible, the cost to the beekeeping industry was estimated at $1.6 million in 1985. Estimated benefits of control to other parts of the rural industry were at least $18.5 million'(Sandrey, 1985). Gorse pollen can be replaced with artificial pollen, therefore, the potential loss to the beekeeping industry does not significantly detract from the net benefits of gorse control.

2.2.2.2 Goat farming

During the early 1980s, when there was interest in goat farming, much research was done on the possibility of using goats to control gorse. 'After burning, grazing gorse re-growth with goats, at high stocking rates, reduced gorse populations to negligible levels within 2 to 3 years'(Radcliffe, 1985).

Goat grazing killed the gorse for several reasons. First, goats ate most, if not all, green material, as well as much non-green plant material. Secondly, goats also ring-barked gorse bushes, which enhanced the death of the gorse bushes. 'Thirdly, the death of gorse bushes was increased by invasion by silver leaf fungus (*Chondrostereum purpureum* (Pers.) Pouzar) into the tissues of goat-damaged gorse'(Radcliffe, 1985). 'This fungus releases a toxin that may eventually kill shoots and entire bushes'(Watts, 1951). 'In one experiment, fruiting bodies of silver leaf fungus were found on dead gorse wood in all treatments, which involved goats but was not found on gorse in sheep-only treatments'(Radcliffe, 1985).

From her work, Radcliffe (1985) gave four recommendations regarding gorse control by grazing management. These recommendations were:

1. the importance of using stock to control gorse growth as soon as practicable after burning;
2. rotational grazing was more effective than set stocking;
3. ensure goats are used in the first summer to prevent gorse spreading; and
4. goats were most effective at a high stocking density.

2.2.2.3 Nurse plants

Many farmers fenced off and abandoned gorse stands that were difficult to manage. This was especially so when returns for wool and meat were very low. Often these areas reverted to native forest that had been sheltered and protected in its early growth stage by gorse. 'However, there is no evidence that gorse is a better protector for native forest regeneration than any other shrub species'(Hill, 1986).

Gorse, broom (*Cytisus scoparius* L.) and kanuka (*Kunzea ericoides* Reichenbach) are all being used as shelter plants for native forest regeneration at Hinewai Reserve, near Akaroa, Banks Peninsula. In the reserve, gorse plants are over 3 m tall but regenerating native plant species are starting to dominate the gorse. Native bush regeneration includes second-growth hardwood forest (tree fuchsia

(*Fuchsia excorticata* (J.R. Forst and G. Forst) L.f), mahoe (*Melicyutus ramiflorus* Forst), five finger (*Pseudopanax arboreus* (Murray) Phillipson) and lacebark (*Hoheria* spp. Cunn.). Several fern species are present as well as scattered podocarps, totara (*Podocarpus totara* Cunn.), matai (*Prumnopitys taxifolia* (D. Don) de Laub.) and kahikatea (*Dacrycarpus dacrydioides* (A. Rich) de Laub.). Hinewai Reserve was a farm but has been allowed to regenerate since 1987 (H. Wilson, pers. comm.). Hinewai Reserve was one of the sites used in these studies (Chapters 4, 5 & 6).

'Conversely, managers of National Parks and Reserves consider gorse among the most significant weed problems in New Zealand'(Hill, 1987). They believe that if the gorse were removed, the spaces could be filled with other more valuable plants, such as native forest understorey, and eventually native forest could regenerate.

'In 1985, a conservative estimate, of the loss of potential production from land occupied by gorse in New Zealand was $22 million per annum. The cost of gorse control was then estimated at $17 million'(Sandrey, 1985). These figures are available because weed control was subsidised at that time and the data were summarized. More recent data are not available because collection ceased when the subsidy ceased in 1985.

> *In 1999, the total defensive expenditures on all pests, excluding bovine TB, was $407.5 million. This figure covers expenditure for central government, regional councils, and the private sector. Regional Council expenditure averaged 14.7% on all weed control, which gives approximately $60 million for defensive expenditure. With the loss of economic output calculated conservatively at 10%, the figure is $40 million. This gives a total estimated cost of weeds in New Zealand of $100 million per year* (Williams and Timmins, 2002). There is no specific breakdown of the money spent on gorse control.

'When the forestry industry was over-sowing with introduced legumes and grasses to suppress weed growth, it was spending $275 ha^{-1} to $355 ha^{-1}. Over 12,850 ha (48% of national total of new plantations) were oversown in this way in 1993 (West and Van Rossen, 1993); over two years this cost $5.3 million.' There is no data available on the treatment of the remainder of the area. 'However, the largest New Zealand forestry company spent $8 million on all aspects of scrub control in 1999'(Williams and Timmins, 2002).

The amount of money that may be saved by the use of biological control is difficult to predict, although potentially the benefits are immense (McFadyen, 1998). Biological control systems are self-sustaining. This means that if large-scale control of gorse were possible by biological methods, it would cease to be a problem in New Zealand.

Potentially, the biological control of gorse will have a negative effect on the gorse hedges that are still used in Canterbury. However, since much land is facing changes in use, e.g., to dairying, many of the hedges are being removed and the farms re-fenced. The removal of gorse hedges and cultivation of areas that were sheltered by the hedges can result in the germination of many gorse seedlings (W. J. Davis, pers comm.). Alternative plants, e.g., *Pinus radiata*, are now being used to replace gorse, as windbreaks.

2.2.3 Forestry

Gorse affects forestry production in many ways, including:

- out-competing with pines in the first few years after planting, therefore, requiring costly control measures;
- affecting the growth rate and quality of the trees through competition for water and trace elements;
- hampering silvicultural activities, such as pruning and thinning, by impeding access to the trees; and
- presenting a greater fire risk than most other understorey plants (Hill, 1987).

2.2.4 Chemical Pollution

As the New Zealand public has become more concerned about the use of chemicals to control pests and weeds in agriculture, the benefits of biological control of gorse to assist farmers are being better recognised. The public has regarded, with suspicion, many herbicides, e.g., those used for gorse control in the past such as 2,4,5 – T. 'Chemical control has often meant the large-scale release of herbicides into the environment'(Hill, 1987).

2.3 Gorse Control

An assessment of the costs and benefits of gorse established the need to control gorse in New Zealand (Sandrey, 1985). Gorse control is difficult to achieve and maintain and there are several methods that may be used, either individually or in combination (Hill, 1987).

2.3.1 Cultural Control

2.3.1.1 Burning

'Fire is a well-established management procedure in New Zealand'(Zabkiewicz and Gaskin, 1978). To be effective, the fire must be very hot so that as many gorse stumps as possible are killed. Following burning, gorse regenerates quickly from buds at the base of the stem and from seeds, which survive the fire by being insulated by the soil. As previously discussed, 'seeds that do not germinate can remain viable for up to 75 years and can become a problem when the soil is disturbed for pasture cultivation'(Popay *et al.*, 1986).

2.3.1.2 Over-sowing

Over-sowing with pasture seed immediately after gorse has been cleared can help minimise gorse re-growth. Competition from pasture species helps to suppress the germination and growth of gorse seedlings. Competition from pasture species also keeps gorse seedling foliage softer for longer. This lengthens the period when gorse seedlings can be eaten by sheep (Popay *et al.*, 1986). Browntop (*Agrostis tenuis* L.) and Yorkshire fog (*Holcus lanatus* L.) are both good competitors (Hartley and Phung Hong, 1979), although they are not highly regarded grasses for pasture production. 'Application of nitrogen fertiliser stimulates vigorous grass growth and makes grasses more competitive but does not produce a response in gorse'(Ivens and Mlowe, 1983).

2.3.1.3 Mechanical Methods

Scattered small gorse bushes can be individually grubbed or dug out, but all of the crown must be removed or there will be re-growth. On flatter land, ploughing or root raking can help but will not remove all crowns and requires a follow-up using

other control methods (Popay *et al.*, 1986). Cultivation of land that has been in pasture for a prolonged period can bring viable gorse seed up to the surface. This can result in many gorse seedlings (pers. obs. W.J. Davis).

An alternative for breaking in country that has been in gorse for a long time is mechanical control. This involves a heavy roller, which is winched up and down the hillside to crush the gorse. This does not kill the gorse plants and further control measures are required. It is normal to oversow the hillside shortly after breaking down the gorse (C.R. Sixtus, pers. obs.).

2.3.1.4 Grazing Management

Sheep eat only the soft shoot growth of gorse; therefore sheep grazing should start when the gorse plants are small. Blocks of gorse should be fenced off into small paddocks so stock can be carried at high stocking rates. 'Gorse seedlings become tall and etiolated if the pasture is allowed to grow tall between grazings, making gorse seedlings more susceptible to grazing'(Popay *et al.*, 1986). Cattle do not give good gorse control. Grazing by goats can be effective in controlling more mature plants (Section 2.2.2.2).

2.3.1.5 Allelopathy

Allelopathy refers to chemical interactions among plants including stimulatory and inhibitory influences. 'These influences may originate from the direct release of toxins from living plants or from decaying plant litter, residues or roots. From this non-living plant material, microorganisms have been implicated in the release of toxins or in the modification of non-toxic compounds to toxic ones'(Ashton and Monaco, 1991).

'There are possibly up to 90 weed species that can interfere with plant growth through allelopathy'(Putnam and Tang, 1986). 'Perennial weeds such as couch (*Elytrigia repens* (L.) Nevski), johnsongrass (*Sorghum halepense* L.) and nutsedges (*Cyperus* spp. L.) are known to be allelopathic'(Ashton and Monaco, 1991). 'There are also several crop plants that are allelopathic, including wheat (*Triticum aestivum* L.), oats (*Avena sativa* L.) and several *Brassica* spp.'(Ashton and Monaco, 1991).

The use of plants that produce allelopathic chemicals to combat weeds is under-used. In overseas research with gorse, it is used as an agent for the control of other weeds. However, there does not appear to be any research into plant allelopathy

being used for gorse control. 'Dicotyledonous weeds may be suppressed for up to two months by the use of mulches of rye (*Secale cereale* L.), wheat and some forage grasses (e.g., *Festuca arundinacea* L., *F. rubra* L. and *Lolium* spp. L.)'(Gavazzi and Paris, 2000).

2.3.2 Chemical Control

The chemicals that are currently used for gorse control are shown in Table 2.1. 'Young gorse plants can be effectively controlled by treatment with some herbicides alone'(Popay *et al.*, 1985). However, 'mature gorse requires the addition of a surfactant to obtain satisfactory wetting and penetration of herbicides into the plant'(Lane and Park, 1984; Stevens *et al.*, 1988). Herbicides may be applied in spring, summer and late winter when gorse is growing rapidly. 'Timing of the herbicide application is critical to give the best control'(Davenhill and Preest, 1986). In the future, there may be chemicals developed that could be applied effectively when biological control agents were not active.

Table 2.1: Current chemicals and their active ingredients used for gorse control (Anon. (2002a); Anon. (2002b).).

Commercial name	Active chemical
Activated amitrole	Amitrole
Amitrole	Amitrole
Answer	Metasulfuron
Buster	Glufosinate-ammonium
Escort	Metasulfuron-methyl
Radiate	Picloram and clopyralid
TAG	Terbuthylazine, amitrole, glyphosate
Tordon Brushkiller	Picloram, triclopyr and ethyl digol
Touchdown	Glyphosate-trimesium
Trounce Gorsekiller	Glyphosate
Versatill	Clopyralid
Weedmaster Dry	Glyphosate

2.3.3 Biological Control

Several fungi attack different parts of gorse plants. A number of them have been screened as potential control agents, both in New Zealand and in Europe. 'As well as fungal agents, there are 94 arthropod species known to attack gorse in Europe but only 16 appear sufficiently host specific to show promise for introduction into

New Zealand as biological control agents. Five of the 16 attack reproductive structures and 11 feed on green shoots. There are no agents that attack gorse roots, crowns or woody stems that are host specific or will not attack New Zealand native flora'(Hill, 1983).

2.3.3.1 Fungal pathogens

'Plant pathogens can be used as biological control agents, utilising either the classical or the mycoherbicide strategy'(Te Beest *et al.*, 1992). Fungi used as mycoherbicides are applied inundatively as a suspension of inoculum and act in a similar way to a chemical herbicide, damaging only susceptible plants that are treated. 'The fungi used are usually already present in the area where the weed is a problem but, because of environmental or seasonal constraints on disease development, do not normally cause serious damage to their hosts under natural conditions'(Johnston *et al.*, 1995). The mycoherbicide approach to biological control relies on recognising and overcoming these limiting factors so that severe disease epidemics are induced on a local scale (Charudattan, 1985).

A survey of fungi associated with diseased stem and leaf tissue of gorse and broom in New Zealand was carried out to isolate fungi that may have potential as mycoherbicides (Johnston *et al.*, 1995). The mode of plant entry and symptoms are shown in Table 2.2.

Table 2.2: Fungi that have been investigated for potential pathogenic control of gorse (Johnston *et al.*, 1994; Johnston *et al.*, 1995).

Fungi	Plant entry	Symptoms
Amylostereum sacratum (G. Cunn.) Burds.	Infected tissues	Patches of disease, affecting woody plants
Ascohyta ulicis (Grove) P.K. Buchanan	Diseased tissue	Tip dieback
Chondrostereum purpureum (Pers.) Pouzer	Through plant wounds	Causes silver leaf disease on horticultural Rosaceous crops
Gibberella tumida P.G. Broadh. & P.R. Johnston	Through leaves	Stem and leaf flecking, stem lesions and tip dieback
Fusarium tumidum Sherb.	Through leaves	Necrotic lesions on stems and leaves

2.3.3.2 Further fungal options

'A *Colletotrichum* sp. is one of the most common xylem endophytes in the United Kingdom'(Fisher and Petrini, 1987). Many biological and cultural features of *Colletotrichum* make species in this genus suitable for development as mycoherbicides. However, *Colletotrichum* was not found in gorse xylem in New Zealand; species of *Microsphaeropsis*, *Phomopsis* and *Pestalotiopsis* were the commonly found xylem endophytes. 'However, none of these fungi caused disease in pathogenicity trials'(Johnston *et al.*, 1995).

Several pathogens tested (e.g., *Microsphaeropsis*, *Phomopsis* and *Pestalotiopsis*) (Johnston *et al.*, 1995) did not cause disease symptoms in greenhouse inoculations or were rarely isolated. Further research may find that some of these are effective, depending on where they are tested. It is possible that some pathogens that were not successful may be useful when different isolates are tested.

2.3.3.3 Goats

Grazing management of gorse, including goats can control gorse (Section 2.2.2.2). Depending on the level of control required, goats could be used either to maintain gorse at an appropriate level, or to eliminate it completely (Radcliffe, 1985).

2.3.3.4 Arthropod biological agents

Several arthropod biological agents have been introduced into New Zealand to control gorse. In addition, there are also native insect species that have adapted to feeding on different parts of the gorse plant. Before the introduction of new agents, they must undergo laboratory quarantine and specificity testing. Table 2.3 shows the arthropods that have been introduced for gorse control, as well as the native insects that feed on gorse. The table also shows the feeding site on the gorse plant and the status of the insect.

Several insects damage different parts of the gorse plant. Some are unsuitable for release in New Zealand because they are not host specific and may damage flora other than the weed species that they are introduced to control.

Table 2.3: Status of biological agents for gorse control gorse in New Zealand (Harman *et al.*, 1996; Anon, 2001).

Biological control agent	Feeding site and impact on gorse	Date of first release
Gorse colonial hard shoot moth* *Pempelia genistella* Duponchel Lepidoptera: Pyralidae	Foliage feeder, limited releases to date, established at one site, impact unknown, further releases planned.	1996
Gorse hard shoot moth *Scythris grandipennis* Haworth Lepidoptera: Scythrididae	Foliage feeder, failed to establish from small number released at one site, no further releases planned due to rearing difficulties.	1993
Gorse pod moth* *Cydia succedana* Denis & Schiffermüller Lepidoptera: Tortricidae	Seed feeder, becoming more common, spreading well, showing potential to destroy seeds in spring and autumn.	1992
Gorse seed weevil* *Exapion ulicis* (Förster) Coleoptera: Apionidae	Seed feeder, common, destroys many seeds in spring.	1931
Gorse soft shoot moth* *Agonopterix ulicetella* Stainton Lepidoptera: Oecophoridae	Foliage feeder, rare, no obvious impact, no further releases planned.	1990
Gorse spider mite* *Tetranychus lintearius* Dufour Acari: Tetranychidae	Sap sucker, common, often causes obvious damage.	1989
Gorse stem miner* *Anisoplaca ptyoptera* Meyrick Lepidoptera: Gelechiidae	Stem miner, native insect, common in the South Island, often causes obvious damage.	is endemic
Gorse thrips* *Sericothrips staphylinus* Haliday Thysanoptera: Thripidae	Sap sucker, becoming more common, slow to disperse, impact unknown.	1990
Aceria genistar Nalepa Acari: Eriophyidae	Foliage feeder, introduced by accident	1985
Ditylenchus dipsaci Kühn* Tylenchida: Anguinidae	Stem and bulb nematode, causes serious stem deformations	

*established

2.3.3.5 *Exapion ulicis* Förster

In an attempt to curb the spread of gorse, the gorse seed weevil, *Exapion ulicis*, was imported into New Zealand from England and released in 1931. 'The weevil became established throughout New Zealand in 10 years'(Miller, 1970). Since then it has destroyed a high percentage of spring produced gorse seed in pods in most areas (Hill *et al.*, 1991a).

'Females lay eggs through a hole chewed in the side of an immature gorse pod. This hole closes and the hatching weevil larvae proceed to destroy the seed in the pod'(Hill *et al.*, 1991a). The adults are released from the pod when it dehisces (Hoddle, 1991). *Exapion ulicis* larvae cannot move between gorse pods and must complete their development in the pod chosen by the adult female. 'Larval survival depends on adult oviposition'(Hoddle, 1991).

Weevils oviposit only in the spring and can infest up to 90% of immature pods. In many areas, the low availability of oviposition sites, coupled with intense pressure on female weevils to deposit eggs, leads to a very high percentage of weevil-infested pods in the spring. 'However, seed produced at other times escape attack, especially where there is abundant autumn flowering'(Hill *et al.*, 1991a).

To control gorse using a seed-feeding species requires the agent to destroy enough seed so that the annual recruitment to the seed bank is consistently less than the amount of seed required to maintain the existing population of gorse plants (Hill *et al.*, 1991a).

2.3.3.6 *Anisoplaca ptyoptera* Meyrick

'*Anisoplaca ptyoptera* is an indigenous stem-boring moth, whose original hosts were members of the genera *Carmichaelia* and *Corallospartium.* It was observed on gorse in the Rakaia Gorge in 1968 where a clump of gorse was unthrifty with many dead branches. The gorse did not flower in the spring and made little growth until autumn each year'(Butler, 1979).

'The moth larvae are most active during September and November, eating phloem and cambium tissue around the stem. Each stem can support up to 10 larvae although four is the usual number. Larvae pupate about January'(Butler, 1979).

'Damage to gorse is evident during the larvae's active stage in the spring. The larvae burrow around the stem, reducing the conducting tissue, sometimes completely ring-barking the stem. Where heavy infestations occur, most gorse bushes are brown with only a few green shoots and spines and no flowering. By December, the gorse bushes were pale green, but signs of the attack were still evident'(Butler, 1979). There was very little green showing in gorse plants at McLeans Island in January 2003 (R.R. Scott, pers. obs.) and they appeared to be dehydrated.

Two factors limit the use of *A. ptyoptera* as a gorse control agent in New Zealand. The first is that native hosts, some of which are rare, may suffer if *A. ptyoptera* populations were artificially increased. Secondly, *A. ptyoptera* larvae suffer a high level of parasitism by parasitoids that are also probably endemic. 'Because local populations periodically crash due to this parasitism, there is only unsustained and sporadic gorse suppression'(Butler 1979; MacCarter and Gaynor, 1980). 'Thus *A. ptyoptera* may be appropriate for consideration as a biological control agent outside New Zealand, where the tribe Carmichealieae and the larval parasitoids do not appear to exist'(Holder, 1992). However, the use of *A. ptyoptera* as a biological control agent overseas may cause other problems. There is a high risk that the case of host jumping from the original host plant to gorse could be repeated in the opposite or another direction, affecting native flora overseas.

2.3.3.7 *Agonopterix ulicetella* Stainton

'*Agonopterix ulicetella* occurs in United Kingdom, the Netherlands, France, Spain and Portugal. In continental Europe, it has been recorded from the three *Ulex* species and on *Genista anglica* L. and *Adenocarpus hispanicus* (Lam.) DC'(Zwölfer, 1962).

It was first considered as a potential biological control agent in 1960 - 61, when it was exported to Hawaii where it underwent host-specificity tests under quarantine. However, there were rearing difficulties (Yoshioka *et al.*, 1992). 'The European International Institute of Biological Control Station in Switzerland conducted preliminary feeding tests in 1963, using second and third instar larvae against a limited selection of test plants. These tests suggested that *A. ulicetella* was highly host-specific extended host-specificity tests were carried out in England and New Zealand between 1980 and 1985'(Hill *et al.*, 1995).

Agonopterix ulicetella is potentially an important biological control agent for gorse. It primarily attacks new growth and a single larva can destroy up to five shoots. It can exist at a high population density, causing serious damage to new foliage. 'Larvae are heavily parasitised in Europe, so this species may achieve higher field population densities in a new environment, such as New Zealand, than in its native range'(Hill *et al.*, 1995).

Lupinus arboreus L. is used in New Zealand for stabilising sand dunes and *Chamaecytisus palmensis* (H. Christ) F.A. Bisbey and K.W. Nicholls is a food source

for grazing animals, bees and some native birds. These plants were not available for the tests in the United Kingdom but tests under quarantine in New Zealand demonstrated that both plant species could be at risk. This delayed the introduction of *A. ulicetella* into New Zealand. '*Agonopterix ulicetella* was released in Hawaii in 1989'(Yoshioka *et al.*, 1992) and is established there. 'This provided the opportunity to test the susceptibility of *L. arboreus* and *C. palmensis* under ambient climatic conditions in large field cages in Hawaii.'

'In those tests, free-flying moths laid few eggs on the test plants, and none developed to produce adult moths. In contrast, gorse plants in the cages were heavily attacked and produced hundreds of moths. Tests in larger cages, outdoors, confirmed that laboratory tests had overestimated the potential host range of the moths and neither plant was at significant risk of attack in New Zealand. With this confirmation of host specificity, and following public consultation, *Agonopterix ulicetella* was released in New Zealand in October 1990'(Hill *et al.*, 1995). 'The soft shoot moth, which feeds on soft new gorse foliage in spring, has been established in Canterbury'(Harman *et al.*, 1996). However, the species has not had an obvious impact on gorse in New Zealand and no further releases are planned.

2.3.3.8 *Sericothrips staphylinus* Haliday

An experiment with gorse thrips, *Sericothrips staphylinus*, in New Zealand was conducted in December 1994. The thrips came from a population cultured outdoors. Releases were made during the oviposition period. 'Gorse thrips has a single annual generation and overwinters as adults on gorse'(Memmott *et al.*, 1998).

One year after release, the bushes were sampled to search for progeny of the released thrips. The thrips had no impact on the growth of the gorse bushes in the first year in the field. 'Neither bush height nor bush width showed any reduction in growth rate with increased thrips density'(Memmott *et al.*, 1998). This experiment showed that field establishment with gorse thrips suffered from a greater proportion of the smaller populations with a high risk of their becoming extinct (Memmott *et al.*, 1998).

Using thrips as an example, a protocol was developed to determine the optimal release size for biocontrol agents. 'When a fixed number of insects is available for release, smaller releases of many small numbers may increase the overall establishment rate'(Memmott *et al.*, 1998).

Sericothrips staphylinus was released in relatively large numbers at all sites and established easily over a wide range of climates in New Zealand and Hawaii. Thrips have not spread far from their release points in New Zealand. Its mode of dispersal is not clear, but a high proportion of brachyptery in adults may be a barrier to short-distance dispersal. 'Thrips from the United Kingdom dispersed poorly in Hawaii and New Zealand, but thrips from Portugal appeared to spread rapidly in Hawaii'(Hill *et al.*, 2001).

Sericothrips staphylinus has now been established in New Zealand and Hawaii for over six years. In the field, bronzing of gorse plants but not plant death has been observed. 'However, it is still not clear if this species will contribute to the biological control of gorse'(Hill *et al.*, 2001). 'In the laboratory, low numbers of adult thrips reduced growth of small plants after only 3 - 4 weeks'(Fowler and Griffin, 1992). However, there is no evidence that *S. staphylinus* can kill mature gorse plants in the field.

2.3.3.9 *Scythris grandipennis* Haworth

Scythris grandipennis is a univoltine moth with solitary larvae that are 1.5 cm long when fully grown. These form complex, 2 cm diameter white webs and larvae forage from these webs to feed on mature gorse foliage from autumn to spring. 'One hundred pupae in webs were released at one site in Canterbury in spring 1993' (Harman *et al.*, 1996). One adult moth was seen shortly after that, but larvae have not since been observed at the site. 'This species has not established in New Zealand'(Hill *et al.*, 1999).

2.3.4.0 *Pempelia genistella* Duponchel

Pempelia genistella is also univoltine and moth larvae are commonly found on mature gorse foliage in autumn. This species is colonial, with 3 - 10 larvae sharing a coarse cream web. 'Larvae overwinter and this strategy may allow the larvae to complete their development in spring on new shoots, which are more nutritious than mature foliage'(Hill, 1982). 'Webs measuring up to 30 cm in diameter have been observed in the field in Portugal, surrounded by heavily damaged foliage. Such webs may have been occupied by successive generations of larvae'(Hill *et al.*, 1999).

This species was identified as being sufficiently host-specific to gorse for introduction into New Zealand. It feeds on foliage and was released into the field in 1996 (Harman *et al.*, 1996). *Pempelia genistella* has been released at two sites (Hayes *et al.*, 1996) but establishment has yet to be confirmed (Hill *et al.*, 1999).

2.3.4.1 *Cydia succedana* Denis & Schiffermüller

The gorse pod moth, *Cydia succedana*, was introduced into New Zealand in 1992. 'Moth stock was collected in Cornwall, England, and Viana do Castello, Portugal, and was released, after several generations in quarantine, for host-range tests'(Suckling *et al.*, 1999). 'In Europe, *C. succedana* has two generations per year. Larvae attack *Ulex europaeus* in spring and other *Ulex* species in autumn. Research into host-specificity was completed in 1991. The first release took place in 1992 and it has become established'(Hill *et al.*, 1999). 'Moths are now abundant at the original release sites'(Hayes, 1999).

'An investigation on a gorse-covered hillside near Darfield, mid-Canterbury, studied the impact of the insect on the annual seed production of gorse where a release of 100 *Cydia succedana* adults and 150 eggs was made in 1992'(Suckling *et al.*, 1999). 'The phenology of gorse reproduction varies greatly with climate and altitude in New Zealand'(Hill *et al.*, 1991a). Position on the hillside affected both plant phenology and insect catch. Though the flowering pattern was similar, the seasonal pod production varied greatly with position on the hillside. 'Pod numbers peaked in autumn (March 1997) at the top of the hill and in spring (October 1997) at the bottom of the hill. The middle area had a pod peak during October 1997. Few plants produced pods in autumn 1998 (February onwards), probably due to a severe drought in the region'(Suckling *et al.*, 1999).

> *There appeared to be two peaks of moth activity, which suggests that there are two moth generations per year. The first peak was in early November, closely synchronised with spring seed production, and arose from diapausing pupae produced in the previous autumn. There was a trough in moth numbers in late November. The presence of some moths throughout the entire period suggests overlapping generations. The second generation peaked in February, before the bulk of autumn pod production in March. This was reflected in low (0 - 10%) levels of pod infestation* (Suckling *et al.*, 1999).

Gorse seed production varies with site-dependent conditions, which means that the impact of this species as a biological control agent will probably vary from place to place. 'Though there was considerable seed predation when pod resources were small (90 - 100%), the overall impact of this insect will rely on its effect on long-term average annual seed production' (Suckling *et al.*, 1999).

2.3.4.2 *Tetranychus lintearius* Dufour

The gorse spider mite, *Tetranychus lintearius*, has shown potential as a biological control agent for gorse. 'Damage to gorse plants by *T. lintearius* is caused by extraction of the cell content of the chlorenchymatous mesophyll' (Stone, 1986). The colonial feeding behaviour of *T. lintearius* resulted in the total chlorosis of tissues that are subjected to gorse mite feeding. 'When the population is high, gorse mites can inflict severe damage to gorse. The first shipment of *T. lintearius* arrived in New Zealand in July 1988 from Cornwall, England. The first releases of mites were in April 1989' (Hill *et al.*, 1989). Since then, the species has been released throughout New Zealand.

It was found that by 1990 the gorse spider mite was only moderately successful in establishing on the West Coast of the South Island and north of 39° S in the North Island. Most poor establishment was in warmer, wetter regions but it was not known what factor was limiting establishment. 'A proposal to introduce a mite strain from a warmer, wetter climate such as northern Portugal or the north of Spain' (Hill *et al.*, 1991b) was implemented. 'Five new mite strains from Spain and Portugal were released, one of which has established itself successfully near Auckland and on the West Coast of the South Island' (Hill *et al.*, 1993).

2.3.4.3 *Aceria genistar* Nalepa

Aceria genistar, a mite species, which feeds on gorse foliage, was accidentally introduced into New Zealand. 'This gorse mite is widespread but has had little apparent impact on gorse growth' (Harman *et al.*, 1996).

2.3.4.4 *Ditylenchus dipsaci* Kühn

Ditylenchus dipsaci, the stem and bulb nematode, is a known pest of crops such as lucerne (*Medicago sativa* L.). This species causes serious stem deformation

of gorse in Westland. 'If the gorse-feeding strain does not attack other plants, it could be distributed to other parts of New Zealand' (Hill and Gourlay, 1990).

2.3.5 Integrated control of *Ulex europaeus*

Before the 1980s, it was thought that one biological control agent would be sufficient to control weeds. There was considerable debate on the practice of multiple introductions versus single species introduction. The belief was that introductions should be made only after elaborate study and, then, only the best species should be introduced (Huffaker *et al.*, 1971). When *Exapion ulicis* was introduced into New Zealand, following this approach, it was expected that this agent alone would control the spread of gorse. However, this did not prove to be the case for a number of reasons. One of these was the occurrence of a second flowering. A second reason was that the active period that the gorse seed weevil active was not always the same as the gorse. This meant that if the gorse was producing seeds either side of the active period of *E. ulicis*, the seeds did not face predation. In the 1980s, much research was done to find which other agents in Europe could be released in New Zealand.

The concept of having a number of different agents attacking the same gorse plant at different times of the year meant that the gorse could become unhealthy and eventually die. If there were just one agent, the plant would be able to recover when the agent was not active, i.e., if a particular agent's presence declined and there were no other agents present.

Integrated control involves more than one method of controlling a pest. The integration of the various methods for gorse control is likely to produce the most effective long-term control. Good pasture establishment and good farming management are essential to maintain good weed control. 'Different methods of weed control include chemical, mechanical and biological control' (Searle, 1989).

2.3.5.1 Toxicity of herbicides to the gorse spider mite

Integration of chemical, cultural and biological control will provide the strategic base for control of pests, plant pathogens and weeds. No single strategy is likely to provide complete control of gorse, (Sections 2.3.1, 2.3.2 and 2.3.3). The effect of chemicals on non-target arthropods is receiving increased attention. However, little field research has been done on this (Theiling and Croft, 1988). 'A

Lincoln study on the toxicity of four herbicides and four surfactants showed that all the herbicide and surfactant combinations, except metsulfuron with Triton X-45, Agral LN or Citowett, were toxic to the gorse spider mite (Table 2.4)' (Searle *et al.*, 1990).

It has been suggested that herbicide applications at lower rates would not be so toxic to the gorse spider mite. 'However, triclopyr and triclopyr/picloram are two herbicides that are likely to be toxic to the gorse spider mite even at low rates, therefore preventing the establishment of the gorse spider mite' (Searle *et al.*, 1990). The likelihood of other biological control agents surviving application of current herbicides would also seem to be very low (A.H. Gourlay, pers. comm.).

Table 2.4: Toxicity of herbicides and surfactants to adult female gorse spider mites 24 h after slide-dip treatment at approximate field rates (Searle *et al.*, 1990).

Herbicide	Deaths (%)	Surfactant	Deaths (%)
Triclopyr	64	Silwett L-77	100
Metsulfuron	7	Agral LN	23
Glyphosate	29	Citowett	24
Triclopyr/picloram	73	Triton X-45	21
Control	2	Control	8

2.3.6 Impact report on *Cydia succedana*

Before the introduction of any biological agent, it is necessary to complete pre-introduction studies, including the distribution and ecology of the weed. 'Preliminary surveys in the colonised regions will indicate to what extent native organisms have become adapted to the feed and what feeding niches on the weed they fill' (Wapshere, 1975).

It is necessary to complete research into the different organisms that are adapted to the weed in question. 'Only organisms that are highly adapted to the weed or its close relatives will possess a combination of specificity and effectiveness that will make them suitable as biocontrol agents' (Wapshere, 1975). It is vital that the control agent selected is the most effective strain of that organism.

An estimation of the effectiveness of any proposed biological agent is necessary. 'Effectiveness can be determined by observation in the weed's native

range in regions eco-climatically similar to the regions that are infested elsewhere' (Wapshere, 1970).

It is vital that the selection of the agent is the most effective strain of that organism. The organisms in any particular geographic locality adapt to the weed form that occurs there. Usually, the provenance of any particular weed form that invades a new region is not known. To discover strains of the organisms that are well adapted to the invasive form of the weed, it is necessary to expose it to strains of the organisms collected over a wide geographic area. 'It is important that the invasive weed to be controlled is exposed to the different strains of the various potential control agents under study to ascertain that they can significantly affect it' (Wapshere, 1975). Modern DNA work has made the testing of different strains of the same biological agent easier as well as quicker.

This approach has been used to direct biological control programmes. One example is *Puccinia chondrillina* Bubak & Syd., which was the most effective agent on skeleton weed (*Chondrilla juncea* L.) populations in the Mediterranean in situations eco-climatically similar to Australian infestation areas (Wapshere, 1970). 'It has proved to be the most effective biological control agent in Australia' (Cullen, 1973; Cullen *et al.*, 1973).

It is essential that the biological control agent will not, after introduction, attack crop plants or plants of social importance. 'It is necessary to demonstrate that the agent will confine its attention to the weed and its relatives' (Wapshere, 1975). The testing regimes for gorse are shown in Table 2.5.

Table 2.5: Centrifugal phylogenetic specificity testing method applied to *Ulex europeaus* (Hill, 1990).

Testing sequence	Plants to be tested
1st	Plants very closely related to the target (Tribe Genisteae)
2nd	Related plants not previously exposed to the agents (NZ native legumes)
3rd	Other related species of importance (NZ economic legumes)
4th	Other plants (e.g. hosts of related pests)

A wide selection of plants within each category was chosen for testing. The larvae of *C. succedana* feed within the pods of their host, therefore the plants tested were principally limited to those capable of forming pods. The exceptions were

Malus sp. Mill. and *Pinus* sp. L., which are the hosts of related *Cydia* spp. These plants are very important economically to New Zealand. Forty-four plant species were tested (Hill, 1990).

> *Three experiments were designed to test the ability of C. succedana to colonise a new host-plant. In order to colonise a new host-plant, an insect must be able to oviposit on it and hatching larvae must be able to complete development on it* (Hill, 1990).

Three tests of specificity were used to test the ability of *C. succedana* to measure this ability. The first was the starvation test, where the larvae did not have any choice in the food that could be eaten. For this, young test species' pods were picked from test plants and placed in Petri dishes. Young gorse pods were set up in a similar fashion. 'Five unfed, first instar *C. succedana* larvae were placed with each group of pods. Pods were checked at five-day intervals to measure larval survival' (Hill, 1990).

> *The second was an oviposition test with a small cage. Two male and three female moths were used for this experiment. Two types of tests were carried out, those with gorse present (choice) and those without gorse (no choice). Experiments were left for three days; the number of eggs laid on each shoot was counted and recorded. For each set of moths, choice experiments were alternated with no choice experiments. There were also experiments set up with gorse alone* (Hill, 1990).

The third test was a large cage oviposition test. This took place outdoors at Silwood Park, Ascot, England. The 17 plant species chosen included those that had had eggs laid on them in the small cage experiments. Eggs were always laid on gorse plants in the choice experiments. In this experiment, six male and nine female *C. succedana* moths were released in each cage. 'The number of eggs laid on each plant after three days was counted and recorded' (Hill, 1990).

> *The response of larvae hatching on test pods was measured. Two shoots of* Sophora *sp., two of Clianthus sp. and two of gorse bearing pods, were exposed to high densities of moths in small containers until eggs were laid on them. Pods were checked seven days after hatching and the performance of the larvae was recorded* (Hill, 1990).
>
> *Transferred first instar larvae fed for several days on the fleshy valves of* Sophora *sp. (kowhai), however, damage to the pods appeared*

insignificant and seeds were not attacked. Similar feeding occurred on Clianthus *sp. but pods and seeds continued to mature normally. When larvae hatched on the pods of both these species, larvae preferred to migrate rather than establish on the pods* (Hill, 1990).
The starvation test showed that some larvae could complete their development on pods of Pisum sativum *L. and* Clianthus *sp. and a small number of eggs were laid on pods in the small cage tests; none were laid on pods on whole plants under more natural conditions. Lentil* Lens culinari *Medic pods were heavily damaged when larvae were placed on them. However, lentil was rejected as an oviposition plant by* C. succedana (Hill, 1990).

'In the small cages, *Sophora* spp. plants had a few eggs laid on them. In larger cages, moths discriminated better, although a small number of eggs were still laid on kowhai pods' (Hill, 1990). 'It is known that experiments similar to those described here overestimate the true host range of an insect species' (Dunn, 1976). When permission was being sought for the release of *C. succedana*, it was thought that *C. succedana* would show better discrimination in the wild. It was realised that there was a possibility that *C. succedana* could cause damage to *Sophora* spp. but it was thought that this would be extremely unlikely (R.L. Hill, pers. comm.).

Field records indicated that the moth was oligophagous in Europe. Minor attack on non-target flowers and pods was recorded in laboratory tests but the apparent host-range narrowed in more natural tests. In New Zealand, *C. succedana* has recently been reared from the pods of several exotic species in the family Fabaceae other than *Ulex europaeus* (A.H. Gourlay, pers. comm.; T.M. Withers, pers. comm.; C.R. Sixtus pers. obs.). However, surveys have not revealed any attacks on native New Zealand species. The outcome of these attacks on exotics appears highly variable and could be caused by a 'spill-over' caused by high moth population densities. There is currently research under way to clarify the extent of the unpredicted non-target impact (Fowler *et al.*, 2003).

2.4 Climate

In New Zealand, gorse grows from sea level to 800 m altitude, from the far north of the North Island to the far south of the South Island (Healy, 1961). In

Europe, it does not survive in arid or continental regions areas where there are temperature extremes (Zabiewicz, 1976) or exposure to cold winds. Optimum gorse growth occurs where the annual rainfall is between 500 and 1,500 mm (Healy, 1961). New Zealand's climate appears to be more favourable for gorse growth than the climate in much of Europe (MacCarter and Gaynor, 1980).

2.4.1 Effect of climate on insect activity

Although not much information is reported on the impact of climate on the release of biological agents for the control of weeds, it is increasingly an important aspect that must be investigated and tested before the release of control agents. For example, the original strain of gorse spider mite was not suitable for release on the West Coast of the South Island and north of 39°S in the North Island. Strains from a warmer, wetter climate (Hill *et al.*, 1991) have since been successful (Hill *et al.*, 1993).

A study of the potential geographical distribution of alligator weed (*Alternanthera philoxeroides* (Martius) Grisebach) and a biological control agent, *Agasicles hygrophila* (Selman & Vogt) (Coleoptera: Chrysomelidae), in New Zealand used a climate matching programme, CLIMEX. CLIMEX indicated that alligator weed had the potential to spread as far south as Christchurch. In addition, previously derived CLIMEX parameter values for *A. hygrophila* were used to indicate regions where the insect would be most active in controlling the weed (Stewart *et al.*, 1995). The biological control insect was introduced into New Zealand in 1981. However, there have been suggestions that the temperatures in New Zealand may be too low for optimum development and overwintering of this species. This factor may influence the effectiveness of *A. hygrophila* as a biological control agent against alligator weed (Stewart, 1996).

Temperature is a major factor that influences the development, fecundity and mortality of poikilothermic organisms. Temperature effects on insects can be placed in two categories. The first relates to the development rate, reproduction and survival of the insect at a given temperature (Stewart, 1996). There have been many studies of this type that have been conducted on both pest and beneficial insects (Gilbert and Raworth, 1996). The second relates to insect survival when exposed to low winter temperatures. There have been many studies where insects have been chilled at

temperatures below 0°C (Baust and Lee, 1981). However, for insects that do not enter a winter diapause, there have been few studies on the effects of chilling insects at non-freezing temperatures (Stewart, 1996). Results for *A. hygrophila* indicated that the low spring and summer temperatures may inhibit population build-up and low winter temperatures may cause high rates of overwintering deaths (Stewart, 1996).

The only monophagous insect known to feed on the annual weed *Emex australis* (Polygonaceae) Steinh. in South Africa, its region of origin, is the weevil *Perapion antiquum* (Gyllenhal) (Scott and Way, 1990). An Australian study using the computer program CLIMEX, determined whether *P. antiquum* would become established in Australia. It was found that high and low temperature stress and low moisture were likely factors that would limit establishment. In Australia, previous unsuccessful release sites had climates that the model indicated were unsuitable for insect release. The most favourable regions for weevil establishment were near the coast in southern Australia. These regions, unfortunately overlap a small part of southern Australian agricultural regions where *Emex* spp. occur (Scott, 1992).

A potential biocontrol agent, *Apion hookeri* Kirby (Coleoptera: Curculionidae), is a candidate for the control of scentless chamomile (*Matricaria perforata* Mérat (Asteraceae)) in Canada. This agent is host-specific. The native range of *A. hookeri* includes a variety of climates. These include a Mediterranean climate with no cold season and summer drought, a temperate climate with a short cold season and rainfall throughout the year and climates with severe and long winters and a summer rainfall peak (Peschken and Sawchyn, 1993). An insect with such a wide range of suitable climates could be an asset when trying to control any particular weed (Crawley, 1989).

2.4.2 Egg and larval instar development of *Cydia* spp.

There has been no research on the effect of temperature on the development of *Cydia succedana* eggs. However, there has been considerable research on other pest species in the genus.

A method of predicting codling moth (*C. pomonella* (L.)) egg hatch was developed using the Californian forecasting model Bugoff 2. This was tested in Germany (4 years) and Italy (2 years). In the first generation (air temperature normally below 30°C), there was agreement between field observations of egg hatch and the model's forecast. However, in the second generation the model gave marked

differences, at both test sites, between field and model forecasts for the second generation. Hatching was three weeks earlier than predicted in Germany, and one week later in Italy (Blago and De Berardinis, 1991).

The link between temperature and *C. pomonella* development rate has been studied in laboratories since the 1920s. Depending on the development stage of the insect, the rate of development increases up to 30 - 32°C and then rapidly decreases (Rock and Shaffer, 1983). In contrast, the Bugoff 2 model had increasing heat units even for temperatures above 32°C (Blago and De Berardinis, 1991).

The rate of development of *C. pomonella* is governed by environmental temperature (Rock and Shaffer, 1983) and is measured more precisely by physiological time (degree-hours or degree-days) than by calendar time (days) (Taylor, 1981). The physiological development time (degree-hours Celsius) for eggs in one study with 10°C as the base temperature, was 2,100 ± 87 degree-hours. These results are comparable with earlier experiments, e.g., Glen and Brain (1982). The egg is a self-contained unit and only needs heat development (Howell and Neven, 2000).

Larval growth rate was retarded when larvae were reared at constant temperatures ≥ 29.2°C. Growth rate was not affected when naturally occurring field-simulated temperatures were used, even when part of the daily temperature was > 34°C (Howell and Neven, 2000). Fifteen percent of larvae reared at 14.8°C under long-days (17 h light:7 h dark) entered diapause. There was no diapause at higher rearing temperatures. Low temperatures of long duration (up to 103 d) apparently induced diapause, even under long days (Howell and Neven, 2000).

To investigate the relationships between pheromone-trap catches, adult emergence and penetration of fruit by the first-instar of *C. pomonella* from 1975 to 1977 was studied in an orchard in south-west England. For the first generation, the time of moth emergence and catch in pheromone traps were not significantly different. The catch of first generation moths in the pheromone traps anticipated the appearance of their larvae in the fruit by 140 - 169 degree-days > 10°C. In the laboratory, eggs hatched after 94 degree-days. However, in the field, wind and sunshine affected the microclimate and the number of day-degrees required for egg development averaged 90 degree-days (Glen and Brain, 1982).

A laboratory study of pea moth (*C. nigricana* (F.)) hatching, found that, when female moths were kept at a constant 23°C, they began to lay eggs 2 - 3 days after emergence, lived for 16 - 21 days and laid an average of 71 eggs. In field cages

individuals survived slightly longer and laid an average of 91 eggs. The estimated developmental zero was 9.4°C at constant temperatures and 8.5°C at fluctuating temperatures. Above 28°C, death rate increased and above 31°C development was retarded. Development at constant temperatures took 6 - 16% longer than in fluctuating temperatures with the same mean temperature (Lewis and Sturgeon, 1978).

Cydia nigricana has become a serious pest in Switzerland where dry, harvested peas (*Pisum sativum* L.) for stock feed were introduced around 1990. Moth hatching starts after 150 day-degrees above 10°C. Flight has been observed from mid May until the beginning of July, when daily average temperatures are above 18°C (Derron *et al.*, 2000).

The rate of development of codling moth life stages depends on temperature and, to a lesser degree, other climatic factors (Glenn, 1922; Shelford, 1927). Other tortricid species, such as the brownheaded leafroller (*Ctenopseustis obliquana* (Walker)), greenheaded leafroller (*Planotortrix exessana* (Walker)),and the light brown apple moth (*Epiphyas postvittana* (Walker)) take longer to develop at lower temperatures as well as taking longer at higher temperatures. Rearing temperature also affected fecundity (Tomkins, 1984).

A study to determine the developmental and survival rate of codling moth at constant temperatures of 16, 21, 27 and 32 ± 1°C in a North Carolina orchard showed that survival rate was highest at 27°C but did not differ significantly among temperatures. Developmental rates increased with rising temperature and there was no evidence of a decline or levelling off of the developmental rate curve up to 32°C. The base threshold was 9.9°C, and 510 day-degrees were required to complete larval and pupal development (Rock and Shaffer, 1983).

A laboratory experiment with codling moth under different temperatures showed that increased temperatures caused a decrease in the minimum exposure time needed to prevent adult emergence. No adults emerged when fifth instars were exposed to 51.0°C for 3 min, no adults emerged when fourth and fifth instars were exposed to 48°C for 20 min (Yokoyama *et al.*, 1991).

Pairs of codling moth not exposed to high temperatures as larvae laid a mean of 73.6 eggs per female with a mean 93.2% egg hatch. Exposure of either of the pair to high temperatures in the fourth or fifth instar resulted in fewer eggs being laid per

female and a lower egg viability. It was concluded that exposure to high temperatures did not cause sterility in adults of this species (Yokoyama *et al.*, 1991).

A further experiment showed that a period of heat followed by a period of cold storage was more effective for controlling the level of *C. pomonella* than either treatment alone. Deaths increased with increased heat intensity and the duration of cold storage (Neven, 1994).

A study of the development and survival of immature stages of *C. pomonella* at 10 constant temperatures between 8.9 and 34.4°C showed that all stages failed to complete development at temperatures below 12.2°C. At 34.4°C, 14% of eggs but no larvae or pupae survived. The lower development thresholds were 10.6°C for eggs, 11.5°C for larvae, 12.5°C for pupae and 11.9°C for egg to adult development. The upper thresholds were near 27.8°C for eggs and pupae, and 32.2°C for larvae. The average number of day-degrees was 529 above the estimated threshold temperature (Pitcairn *et al.*, 1991).

There have been studies of various pest members of the genus *Cydia* and it appears that the lower development threshold is approximately 10°C and the upper threshold is approximately 28°C.

2.5 Conclusions

Gorse is a noxious weed that costs the New Zealand economy many millions of dollars annually. Gorse has some beneficial aspects but it has been shown that the benefits of gorse are far outweighed by its negative aspects. Many of the beneficial aspects of gorse will still be retained despite the introduction of several biocontrol agents. This is because biological control will not eradicate gorse.

Integration of different control tactics may assist in obtaining better gorse control. This integration could involve mechanical methods, various insect agents and goats. The use of chemicals could also assist. However, at present, the herbicides used are toxic to biological control agents. Further research into potential chemicals may develop an active agent that is not harmful to beneficial insects. Alternatively, chemicals could be applied when the various biological agents are not active.

There is a limit to the number of biological agents that can be released in New Zealand. This is because many possible agents will attack flora other than gorse.

There have been releases of biological control agents where the agent has not become established in New Zealand. This may be due to climate variation, which can be investigated with programs such as CLIMEX. It has been found that different insect strains, from different regions, are suited to different climate types.

Research has shown that the temperature threshold effects on development of instars of *C. succedana* are minimal. The lower development threshold for other members of the genus *Cydia* appears to be approximately 10°C, therefore it is assumed that the threshold for *C. succedana* is also probably around 10°C. The upper temperature limit of other *Cydia* species is approximately 28°C. Other species have been shown to have 4 - 6 instars, depending on climatic conditions. Laboratory tests appear to give a different numbers of instars compared with field results. It can be assumed that the number of instars would be similar in *C. succedana.*

Chapter 3

Aspects of Egg and Larval Biology of *Cydia succedana*

3.1 Introduction

As discussed in Chapter 2, gorse has been a noxious weed in New Zealand since 1900 (Moss, 1960). In many parts of New Zealand, gorse has two reproductive generations each year. To combat the problem of gorse, the gorse seed weevil (*Exapion ulicis*) was introduced into New Zealand in 1931 (Kuschel, 1972) and is now widespread. However, this biological control agent has only one generation per year. The weevil can destroy a high percentage of spring-formed gorse seed (Miller, 1970) but the second generation of gorse seeds were not biologically controlled.

Chemical control methods were developed during the late 1940s and were the main control for gorse until recently (Rees and Hill, 2001). However, due to the public becoming more aware of the toxicity of chemicals used to control weeds, the concept of biological weed control has surged ahead. There has been a concentrated effort to implement biological control of gorse both in New Zealand and other countries where Europeans settled in the nineteenth century. The effort to control gorse has resulted in the introduction of several biological control agents, each attacking different parts of the gorse bush.

Cydia succedana was released in 1992 and has become established, as outlined in Section 2.3.4.1. There has been very little research on the development of the eggs and larvae of *C. succedana*. However, as outlined in Section 2.4.2, there has been considerable research on other species of the same genus that are pests, especially codling moth (*C. pomonella*), and these studies of the development on *C. succedana* were based on previous research on *C. pomonella.*

There has been no research on the amount of gorse seed that is damaged by larvae of *C. succedana* in Europe and very little in New Zealand. However, there has been research on other species of the same genus. The pea moth (*C. nigricana*) is similar to *C. succedana* because it feeds on legume seed and this study was based on previous experiments with pea moth. Those experiments on the pea moth indicated that it damaged one pod per larva (Bradley *et al.*, 1979; Emmett, 1982; Emmet, 1988). There was no indication on the amount of pea seed that *C. nigricana*

consumed. Bradley *et al.* (1979) found that *C. succedana* larvae moved from pod to pod but there was no indication of the number of pods that *C. succedana* damaged, nor of the amount of seed consumed.

The aim of the first part of this study was to ascertain the activity threshold temperatures for the development of the eggs and larvae of *C. succedana*. The second aim was to determine the number of larval instars. The third was to investigate the number of gorse pods that were damaged by *C. succedana* larvae under laboratory conditions.

3.2 Materials and Methods

3.2.1 Capturing moths

Moths were caught on 6 October 2003 at McLeans Island, Canterbury, New Zealand (43° 28.05' S 172° 28.46' E) with the use of sweep nets. Moths were put in plastic bottles from the nets and then placed in chilly bins with cool pads to keep the moths calm and cool.

On return to the laboratory, the plastic bottles were placed inside a large clear Perspex cage and left overnight for the moths to emerge. The temperature in the laboratory was constant at 3°C, with a 16:8 h light:dark cycle. The following day, the moths were sexed and two females and one male were placed in biscuit barrels. The biscuit barrels were then placed in a warm laboratory, which operated with set temperatures: 22°C light, 18°C dark, with a 16:8 h light:dark cycle. In each biscuit barrel, there were 2 - 3 moistened dental rolls and a shoot of gorse that had 2 - 3 seed pods as well as some spines (Plate 3.1). Shoots were changed daily.

Gorse pods and spines were inspected for eggs daily (Plate 3.2). Five eggs were placed into a Petri dish. The eggs were not separated from the pods or spines. Petri dishes contained a filter paper that had been moistened with sterilised water.

Plate 3.1: Biscuit barrel set up for *Cydia succedana* moths to lay eggs.

3.2.2 Egg development

Petri dishes were placed in incubators that operated at constant temperatures of 8, 12, 16, 20, 24, 28 and 32°C with a 16:8 h light:dark cycle. Dishes were inspected daily and sterilised water was added if the filter paper was dry. Eggs becoming dehydrated in Petri dishes at higher temperatures were a problem. To overcome this, a trial was carried out with eggs placed in sealed plastic containers. The moths for this were caught on 10 November at McLeans Island. For this trial, the incubators operated at constant 8, 12, 16, 20, and 24°C. Maximum and minimum thermometers were placed in the plastic containers to record the daily temperatures.

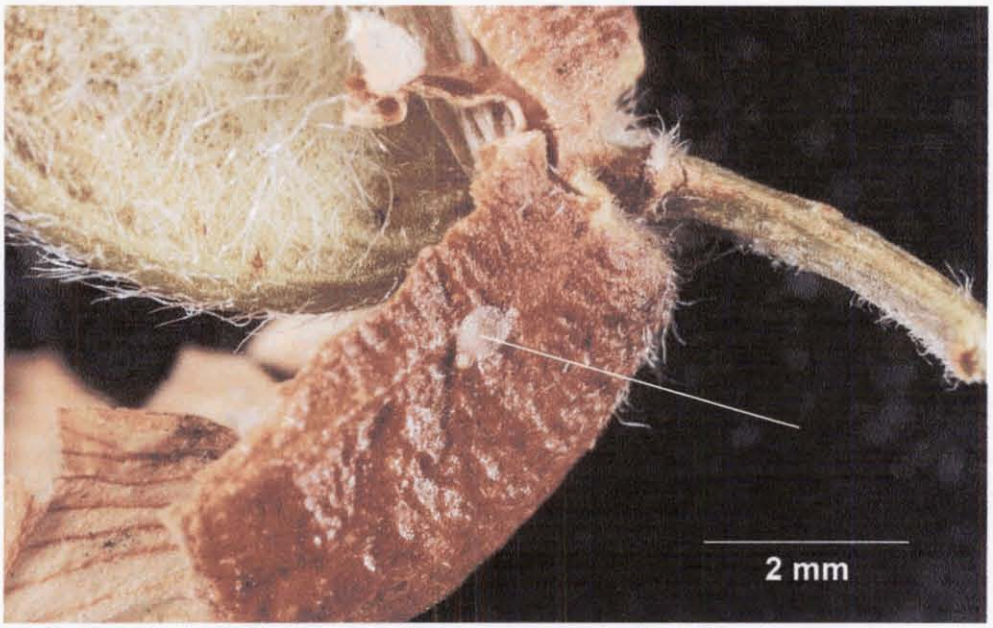


Plate 3.2: Freshly laid *Cydia succedana* egg on the calyx of a gorse pod.

3.2.3 Larval development

For the intended method of this study, larvae were to be fed on an artificial diet in a test tube. This experiment was to occur with hatched larvae from each temperature incubator that was used for the egg development study. However, due to the failure of the original egg development trial there were no larvae hatched to continue the larva development study.

First-instar larvae from another source were then used for this study. Larvae were placed in fertilised flowers, which were placed in the test tubes of artificial diet, approximately in the middle of the test tube. Half a dental roll was placed in the test tube opening to prevent the larvae from escaping. Thirty-five test tubes were placed in ice cream containers, with one ice cream container placed in each incubator, operating at 8, 12, 16, 20, 24 and 28°C on 22 October 2003. The test tubes were arranged in each incubator so that the artificial diet was at the top. This was because the larvae tended to go to the top.

3.2.4 Number of instars

Some first instar larvae were preserved in alcohol. The remaining larvae were placed in test tubes with a fertilised flower and artificial diet. Larvae were placed in a constant temperature incubator at 20°C, and 16:8 h light:dark. Larvae were taken out and placed in alcohol when they exited from the fertilised flower. The remaining

larvae were left until they had finished the artificial diet when they were placed in alcohol. To complement the larvae from the laboratory, samples were collected from McLeans Island and Golden Bay.

To determine the number of instars in the larval stage of the *C. succedana*, head capsule width was measured under a binocular microscope (112.5 × magnification) fitted with an eyepiece graticule.

The 96 units that were shown on the eyepiece graticule were equal to 1.7 mm. Therefore, 1.7 mm divided by 96 units gave the number of millimetres in one unit (0.0178 mm). This was multiplied by the number of units of each head capsule width to give head width in millimetres.

Dyar's rule was used to determine the number of instars present in the larval stage of *C. succedana* by multiplying the smallest recorded average size by 1.4 and this was repeated (Wigglesworth, 1972).

3.2.5 Consumption of gorse pods

On hatching, 10 larvae were placed in individual clean test tubes with a fertilised gorse flower. The test tubes were placed upside down in a test tube rack. Only 10 larvae were available for this trial due to the difficulty in raising larvae. The test tube rack was placed in an incubator at a constant temperature of 20°C, with a 16:8 h light:dark cycle.

After the larvae exited from the flower, a green gorse pod was placed in the test tube. This was repeated after the larvae exited from the pod until the larvae pupated.

3.2.6 Data collection

Data were graphed using Sigma Plot 2001. There was no statistical analysis because there were no replicates.

3.3 Results

3.3.1 Egg development

Although in the first trial no eggs completed development, some results were obtained. At 32°C, the Petri dishes, as well as the eggs, were quickly dehydrated. At

28°C, some eggs showed some development, the eggs became red from 15 October (6 days). Few eggs showed this development (10/25 eggs). Some eggs (7) at 24°C showed the same signs of development from 17 October (10 days), but there was no further development. At 20°C, two eggs showed some swelling on 19 October (11 days) but there was no further development. There were no signs of development at the other temperatures.

In the second trial, where the gorse pods and shoots were placed in sealed plastic containers, daily maximum and minimum temperatures were recorded (Table 3.1). Temperatures were recorded until there was no further egg development. The incubator at 8°C did not produce any larvae by 21 days, and the experiment was terminated. The temperatures fluctuated, usually only by 1 - 2 degrees but the incubator set at 8°C fluctuated from a minimum of 4°C to a maximum of 12°C. The time for eggs to develop under the various constant temperatures are shown in Figure 3.1. From these data the threshold temperature for egg development was calculated (Figure 3.2a).

3.3.2 Larval development

The results showed that the fastest larval development was at 28°C, where the first larvae emerged from the fertilised flower in five days. The larvae at this temperature consumed most of the artificial diet in the tube within three weeks of emerging from the fertilised flower. Larvae emerged from fertilised flowers at cooler temperatures after longer periods in the fertilised flowers; the mean times are shown in Figure 3.1. At all temperatures, a high percentage (≈ 70%) of larvae died in the fertilised flower stage. Only larvae at 28°C pupated but the pupae were not reared to eclosion.

To find the threshold temperature, the development rates against the temperatures were used. The development rates were calculated using the formula: 1/ number of days for development of eggs or larvae

The correct intercept formula is $y = a + bx$, where a is the intercept and b is the slope, but as there no replicates in this study, a statistically sound result could not be obtained. The number of degree-days required for development was calculated using the formula 1/b (Figure 3.2)

Consumption rate of the artificial diet varied with incubator temperature. At the highest temperature, 28°C, most of the artificial diet was consumed within two to

three weeks of emergence from the fertilised flower, although not many larvae reached pupation. These results are shown in Figure 3.2a. The egg development threshold was approximately 11.5°C. Figure 3.2b shows the threshold for larval development from emergence from a fertilised flower where the threshold temperature was 14°C. Included in this graph is the larval developmental rate for larvae that were reared at 28°C. When the developmental rate for 28°C was excluded, the threshold temperature was approximately 11.5°C (Figure 3.2c). This exclusion was investigated because it appears that 28°C is past the point of inflection on the sigmoid development curve, where the curve begins to flatten out (Figure 3.2c).

Table 3.1: Daily minimum and maximum temperatures inside plastic sealed containers in incubators set at various temperatures.

Day	8°C		12°C		16°C		20°C		24°C	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
1	5	10	12	13						
2	6	9	12	12	14	17				
3	6	8	12	13	15	16	19	21		
4	4	12	11	14	16	16	19	20	23	25
5	5	11	12	12	16	16	18	23	23	25
6	7	10	12	13	16	16	21	23	23	25
7	8	8	12	13	16	16	21	22	23	24
8	8	8	12	13	13	16	20	21	23	24
9	5	10	12	12	15	16	20	20	20	23
10	5	9	12	12	12	15	20	20	20	23
11	4	12	12	13	9	16	20	20	20	24
12	5	10	12	13	13	16	20	20	20	22
13	4	10	12	12	13	16	20	20	19	23
14	6	10	12	12	14	15	20	20	19	23
15	4	12	12	14	13	15	20	20		
16	4	12	12	14	13	15				
17	4	10	12	13	14	17				
18	5	11								
19	5	11								
20	5	11								
21	5	10								

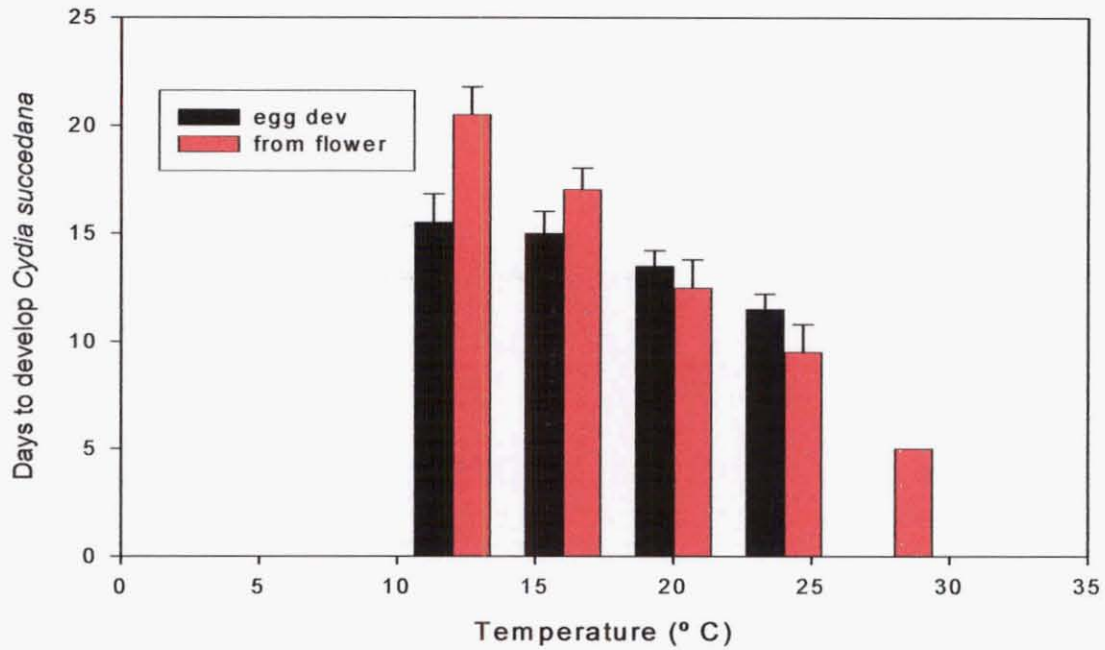


Figure 3.1: Development of *Cydia succedana* eggs and larvae under different constant temperatures. I = SE

3.3.3 Number of instars

From the few samples that could be measured it appeared that *C. succedana* has six larval instars. The smallest head capsule width recorded was 0.35 mm and the largest was 2.00 mm. Using 0.35 mm as the first instar then multiplying by 1.4, five multiplications were required to cover all of the head sizes that were obtained in the collected samples, giving a range of 0.35 to 1.88 mm. A group of larvae is shown in Plate 3.3.

3.3.4 Consumption of gorse pods

Larvae emerged within 11 days of being placed in a fertilised flower. Larvae then entered a green gorse pod and destroyed all of the seed in it. After all the seeds were consumed, larvae emerged through round holes chewed in the side of the pod and sought another pod. Plate 3.4 shows the exit hole of a larva through the side of a gorse pod.

In one case, five first-instar larvae emerged from fertilised flowers and sought a gorse pod. Of these larvae, four emerged from the first pod and sought a further

pod. Three larvae emerged from the second pod and entered a third pod. None of the larvae that emerged from the fertilised flowers pupated.

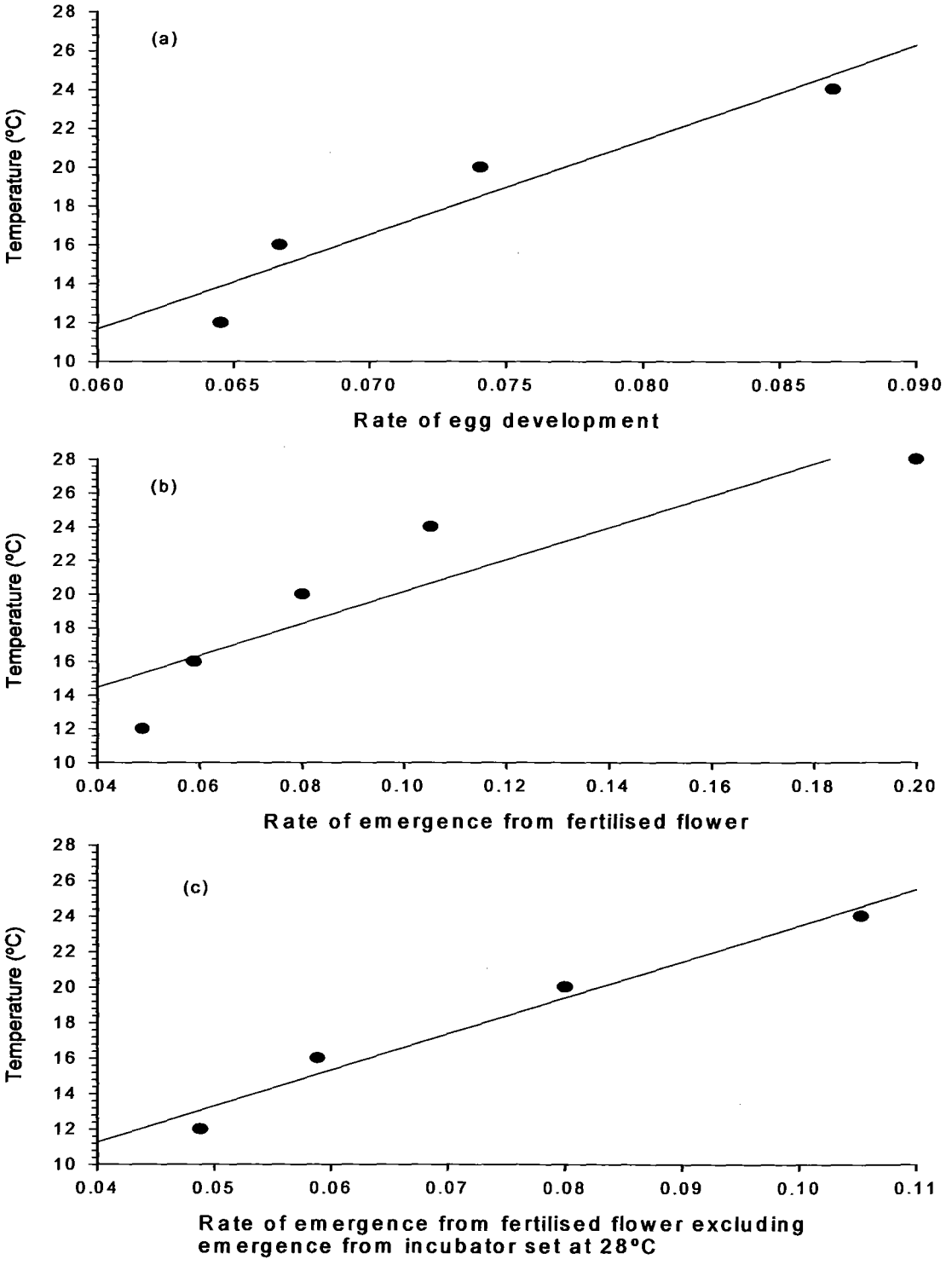


Figure 3.2: Threshold temperatures for development of *Cydia succedana.* (a) Egg development. (b) Larval development. (c) Larval development with rate for 28°C omitted.

Plate 3.3: A group of *Cydia succedana* larval instars, left to right; 6^{th} -1^{st}.

Plate 3.4: Gorse pod with an exit hole of *Cydia succedana* larvae at the far right.

3.4 Discussion

The purpose of these studies was threefold: first to find the threshold temperature for egg and larval development. Second, to find the number of instars that *C. succedana* larvae go through. Third, to ascertain the number of gorse pods that were damaged by *C. succedana* larvae. This would then assist in calculating the percentage of the annual gorse seed production that was damaged by *C. succedana* in the field. This information could then be used to decide whether it was necessary to introduce further gorse seed-feeding biological control agents into New Zealand to control the spread of gorse, especially in areas of widespread gorse infestation such as at Hinewai Reserve. However, due to the difficulty in rearing moth larvae, there were insufficient larvae to provide replicates. Therefore, there were not any definite answers to the questions for this chapter.

The development of eggs of the genus *Cydia* has been studied thoroughly for some pests such as *C. pomonella*. Rock and Shaffer (1983) found that the threshold temperature for codling moth was 9.9°C and 510 day-degrees were required to complete larval and pupal development. The base temperature was very close to the 10°C threshold, which has been widely used in many studies of *C. pomonella* (Glenn, 1922; Riedl and Croft, 1978). The threshold temperature for *C. succedana* egg and larval development in the current study was 11.5 °C, which is reasonably similar to that of *C. pomonella*. However, as there were no replicates, it is not known if this single observation is at the top or bottom of the natural range, i.e. there is no standard deviation and, therefore, it cannot be ascertained with any confidence how close the temperature threshold for *C. succedana* is to that of *C. pomonella*.

The day-degree requirement of for *C. pomonella* at 510 day-degrees (Rock and Shaffer, 1983) was higher than reported in other studies of the same moth, e.g., 437 day-degrees (Riedl and Croft, 1978), but was similar to the 521 day-degrees used by Glenn (1922). For *C. succedana*, degree-days were calculated to be 588 degree-days to reach the pupa, and this is considerably higher than results obtained for *C. pomonella*. Previous experiments on *C. pomonella* development showed that the pupal stage lasts for 11 to 20 days (Pawar *et al.*, 1982) and, although the current study did not test this, it would be reasonable to assume that the pupal stage for *C. succedana* would also fall into this time frame, depending on the ambient temperature.

The egg development study showed there was a minimum temperature, below which no egg development occurred. There was no egg development in the incubator set at 8°C, indicating that the threshold was between 8 and 12°C. Unfortunately, it was not possible to determine the maximum temperature threshold for egg development.

The original quarantine tests of *C. succedana* saw eggs hatch at approximately 12 days after deposition, operating with the 16:8 light:dark cycle at a constant 16°C (Hill and Gourlay, 2002). In this study, eggs hatched after 12 to 14 days, depending on the temperature. The fastest egg development, 12 days, was at 24°C, and the slowest was at 12°C (Figure 3.1).

The survival of *C. pomonella* from neonate larvae to newly emerged adults varied from 36.7% to 46.7%, with the highest survival occurring at 27°C (Rock and Shaffer, 1983). However, other studies have reported a survival rate as high as 90% (Rock, 1967) and as low as 22.5% (Geier and Breise, 1978). The development and survival of *C. pomonella* at 10 control constant temperatures, between 8.9° and 34.4°C was tested. All stages failed to complete development at temperatures below 12.2°C and at 34.4°C no larvae or pupae survived (Pitcairn *et al.*, 1991).

It is known that first-instar larvae are susceptible to desiccation (Hill and Gourlay, 2002), which is supported by the current study. This study showed that there was a poor survival of larvae that emerge from fertilised flowers (≈ 25%) and very few larvae survived to pupation under any temperature regime. This may have been due to the food that they were fed, general rearing medium artificial food manufactured by HortResearch.

A study on the impact of rainfall on the mortality of *C. pomonella* larvae showed that they were positively correlated. The greatest mortality (18.2%) occurred in the first-instar, when they were just beneath the epidermis of the fruit (Hagley, 1972). Although such an impact was not observed in this study, climate would have an impact on larval survival, especially first-instars. This is likely the case, especially in areas that have a high rainfall (Appendix 2). This would be because, with a heavy rainfall, eggs could be washed off the plant. In addition, first-instar larvae, which would be searching for a fertilised flower or gorse pod and, if there were consistent rain, they also could be washed off. The annual rainfall at Bainham was considerably higher than at the other Golden Bay sites (Appendix 2). There was a corresponding

relationship with the percentage of damaged gorse pods. Fewer gorse pods were damaged at Bainham than at the other Golden Bay trial sites.

Much research has been done on the number of larval instars in various *Cydia* pests. An example is oriental fruit moth *Grapholita molesta* (Busck) (cited as *C. molesta*), which has five larval instars. This study used head-capsule widths and developmental time for each instar (Yokoyama *et al.*, 1987). It was shown that *C. molesta* had five larval instars when reared at various temperatures. Instars could be distinguished by the head-capsule width (Russell and Bouzouane, 1989).

Head-capsule width has been used as an indicator of larval instar in *C. pomonella*. Head capsule width correlated with larval instar in a study in Michigan, United States. Average head capsule widths were 0.33, 0.50, 0.82, 1.18 and 1.55 mm from the first to the fifth instars (Weitzner and Whalon, 1987). However, these average head-capsule widths increased by more than 1.4 from one instar to the next. Alternatively, the measurements suggest that one instar was missed in the measurements; probably around 0.64 mm. It was found that measurements of days and day-degrees were more variable than head-capsule width as a method of estimating larval instar (Weitzner and Whalon, 1987). In a study, in India, it was found that there were five or six larval instars (Pawar *et al.*, 1982).

Studies of pests in the *Cydia* genus have found five to six instars, and it was expected that the measurements for *C. succedana* would also have that number of instars. The limited number of measurements that were available in this study ranged from 0.35 mm to 2.00 mm, which covered the proposed six instars. However, due to the small number of specimens to measure, further measurements are required to confirm that there are six instars.

The amount of seed eaten by pest insects can affect a producer's viability. The pea moth (*C. nigricana*) is a serious pest of peas in England and Europe; the larvae of the moth reduce the economic value of crops. Dry harvested peas are damaged more because they are harvested later and exposed to attack for longer (Emmett, 1982).

In crops of common vetch (*Vicia sativa* L.) in England, *C. nigricana* and *C. lunulana* (Denis & Schiffermüller) larvae consume or damage every seed in the pod in which they develop (Koptur, 1998). The moths of *C. nigricana* and *C. succedana* are a similar size (Bradley *et al.*, 1979), so it was assumed that the larvae would damage similar amounts of seed. *Cydia nigricana* damages the seed in

one pod but, for the larvae of *C. succedana* to damage a similar amount of seed, it would be necessary to damage seed in several pods. Therefore, it was assumed that, under laboratory conditions, *C. succedana* would damage all the seeds in at least one pod (average 7 – 8 seeds), therefore reducing the amount of viable annual gorse seed produced. In the current field investigations, *C. succedana* damaged up to 45% of the sampled pods and approximately 80% were damaged by *Exapion ulicis* (Chapter 5). However, it could not be ascertained how many larvae of these biological control agents were responsible for the percentage of seed damaged.

Hill and Gourlay (2002) found that after the larvae consumed all of the seed in one pod, they exited through round holes chewed in the side of the pod and sought another pod (Plate 3.4). Approximately 80% of first-instar larvae transferred to a second pod, and 70% of those larvae pupated successfully (Hill and Gourlay, 2002).

Larvae could complete the first instar without penetrating a pod by feeding on detritus within the degenerating flower (Hill and Gourlay, 2002). To investigate this, first-instar larvae were given a fertilised flower in order to feed on the detritus. When the larvae had eaten all of the food material inside the fertilised flower, they emerged. Upon emergence, a green gorse pod was placed in the test tube and this was repeated until they did not emerge.

The results of this study indicate that *C. succedana* larvae each consume 2 – 3 gorse pods but, because of small numbers of larvae, there were no replicates and only one larva entered a third pod. Therefore, the result has to be treated with caution. Further study should also take into account the number of seeds in each pod, as this may have a direct bearing on the number of pods that are attacked by the larvae. Intact pods in Golden Bay averaged approximately eight seeds, whereas pods from southern sites had fewer seeds (average approximately five) (Appendix 4). This may result in larvae attacking fewer pods in areas where the pods contain more seed.

Partially damaged seed can still germinate, as shown by Sixtus *et al.* (2003a) (Appendix 6). In addition, Koptur (1998) found that vetch seed that had been damaged by *C. nigricans* still germinated. Therefore, it is possible, that if the *C. succedana* larvae either died or exited a pod before completely destroying the seeds, the seeds may still germinate if conditions outside the pod were favourable.

3.5 Conclusions

The results of this study indicated that the lower temperature threshold for *C. succedana* was 11.5°C for both egg and larval development. The day-degrees needed for egg and larval development were 588. This value is higher than results obtained on similar tests of different pest species in the same genus but there were no replicates that would give some indication of the variability of this result.

The survival of *C. succedana* was low (≈ 25%) at all temperatures and previous studies of other members of the same genus, e.g., *C. pomonella*, also have a low survival rate, although not as low as in this work.

The number of larval instars was determined using head-capsule width measurements. From the limited information obtained, the number of instars was calculated to be six, although more samples are required to confirm this. Previous investigations with other species of the same genus have found them to have 5 – 6 instars.

The number of gorse pods damaged by *C. succedana* larvae, in the laboratory seems to be 2 – 3, after having a fertilised flower for the first instar. There may be a difference in the number of pods damaged in different climatic zones. For example, gorse pods at Golden Bay sites had more seeds in undamaged pods than the pods sampled from southern sites.

Chapter 4

The Phenology of *Cydia succedana* on Gorse in Canterbury

4.1 Introduction

In order to obtain an understanding of the effectiveness of the gorse pod moth (*Cydia succedana*) in New Zealand, it is necessary to study its phenology, as well as the phenology of its host, gorse (*Ulex europaeus*). Insect phenology is the study of life cycle phenomena such as timing of egg laying in relation to climate or the availability of the food source. Plant phenology includes the study of growth from leaf burst to leaf fall as well as the reproduction of the particular plant that is being studied.

The phenology of gorse reproduction varies greatly with climate and altitude in New Zealand (Hill *et al.*, 1991a). Development rate of *C. succedana* is modified by several factors, such as photoperiod and solar radiation, but it is primarily affected by temperature (Rock and Shaffer, 1983), since it is a poikilothermic animal.

There has been some study on the gorse pod moth in New Zealand as discussed in Section 2.3.4.1. In this earlier research there appeared to be two peaks in moth activity, which indicated that there were two generations per year (Suckling *et al.*, 1999).

The aim of this part of the study was to compare moth phenology in a warm, dry area, McLeans Island, with a cooler, wetter area, Hinewai Reserve, Akaroa, using pheromone traps, as well as determining the synchronicity of the moth phenology with that of gorse. The gorse plants at McLeans Island were spread throughout an area of pasture. At Hinewai the gorse was dense. Both sites had gorse plants which were at a suitable density. Both sites were chosen for this part of the study due to their proximity to Lincoln University.

4.2 Materials and Methods

4.2.1 Sampling sites

Five pheromone traps were set out randomly at both McLeans Island on 6 March 2002 (43° 27.99' S 172° 28.97' E, 60.2 m above sea level) and Hinewai on 8 March 2002 (43° 48.62' S 173° 01.67' E, 469 m above sea level). Individual sample references and altitudes are given in Appendix 1. Traps were inspected regularly until 19 March 2003. The daily minimum and maximum temperatures and daily rainfall were recorded during the experiment (Appendices 2 and 3).

At Hinewai Reserve, the gorse was very dense and was not controlled, because it was a part of a native flora regeneration programme. The soil types at Hinewai are Stewart-Summit soils. The topsoil is a very dark brown loam, which is very friable. At McLeans Island, gorse had spread intermittently into a pasture and its growth was impeded, due to the shortage of moisture and attack by several biological control agents. The soil type in this area is a recent Selwyn, which is a very stony sand soil (Cox and Mead, 1971).

Five traps were baited with (E, E)-8,10-dodecadien-1-yl acetate, which had been tested in previous experiments (Suckling *et al.*, 1999). The bait used attracts only male moths. The traps were checked weekly to monthly, depending on moth activity. Changing the base depended on the activity of the moths. When they were very active, (March/April and November/December), the bases were changed weekly. At other times, they were changed every two to four weeks. The pheromone caps were changed every six weeks as recommended by HortResearch. A pheromone trap is shown in Plate 4.1. It shows the bait and the sticky surface inside the trap and Plate 4.2 shows the exterior of a pheromone trap.

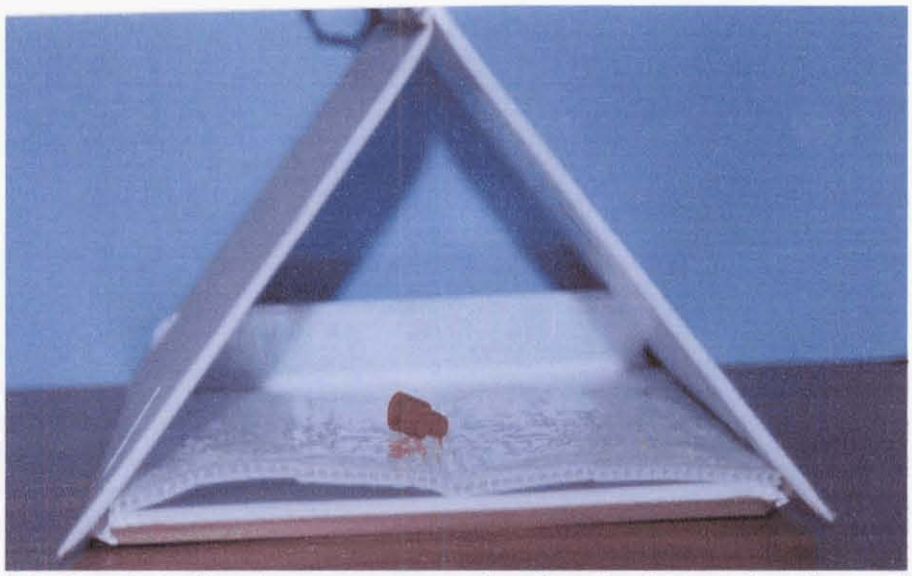


Plate 4.1: Interior of a pheromone trap, showing the bait and sticky surface on which male moths were trapped.

Plate 4.2: Exterior of a pheromone trap.

The number of male moths trapped was counted from each pheromone trap each time the base was removed. Some dead moths were removed and inspected to ensure that they were *C. succedana*.

4.2.2 Data collection and analysis

The data were graphed using the Sigma Plot 2001. Data were analysed using analysis of variance with the SYSTAT 9 package. Least Significant Difference was calculated using Greenhouse-Geiser with ANOVA from repeated measures.

4.3 Results

Hinewai Reserve has an average rainfall of 1650 mm. During the 13 months of the study, there was a total rainfall of 1512 mm, i.e., slightly less than the average rainfall. McLeans Island has an average rainfall of 616 mm and again there was a slightly less than average total rainfall of 574 mm, during the 13 months of the experiment (Appendix 2).

For temperature, the daily maximum and daily minimum, temperatures were compared for the two sites. There was a significant difference between the two sites in daily maximum and minimum temperatures (maximum $P < 0.0001$ and minimum $P < 0.0001$). The monthly average maximum and minimum temperatures and the monthly total rainfall for the 13 months of the experiment are shown in Figure 4.1. There was also a difference between the two sites in the rainfall records but there was no analysis of this because there was only one figure for each month. The daily maximum and minimum temperature are shown in Appendix 3.

At McLeans Island, the months with the highest rainfall were April, June and November where the monthly totals were approximately 85 mm. The remaining months had totals between 25 and 45 mm, with the exception of July (20 mm) and February (12 mm). Hinewai Reserve had a heavier rainfall with the highest monthly totals being over 150 mm. The months with heavy rainfall were April, May, June, August and November 2002 and March 2003. March, July, October and December 2002 had monthly totals of between 75 and 100 mm. The monthly totals for September 2002 and January 2003 were just over 50 mm.

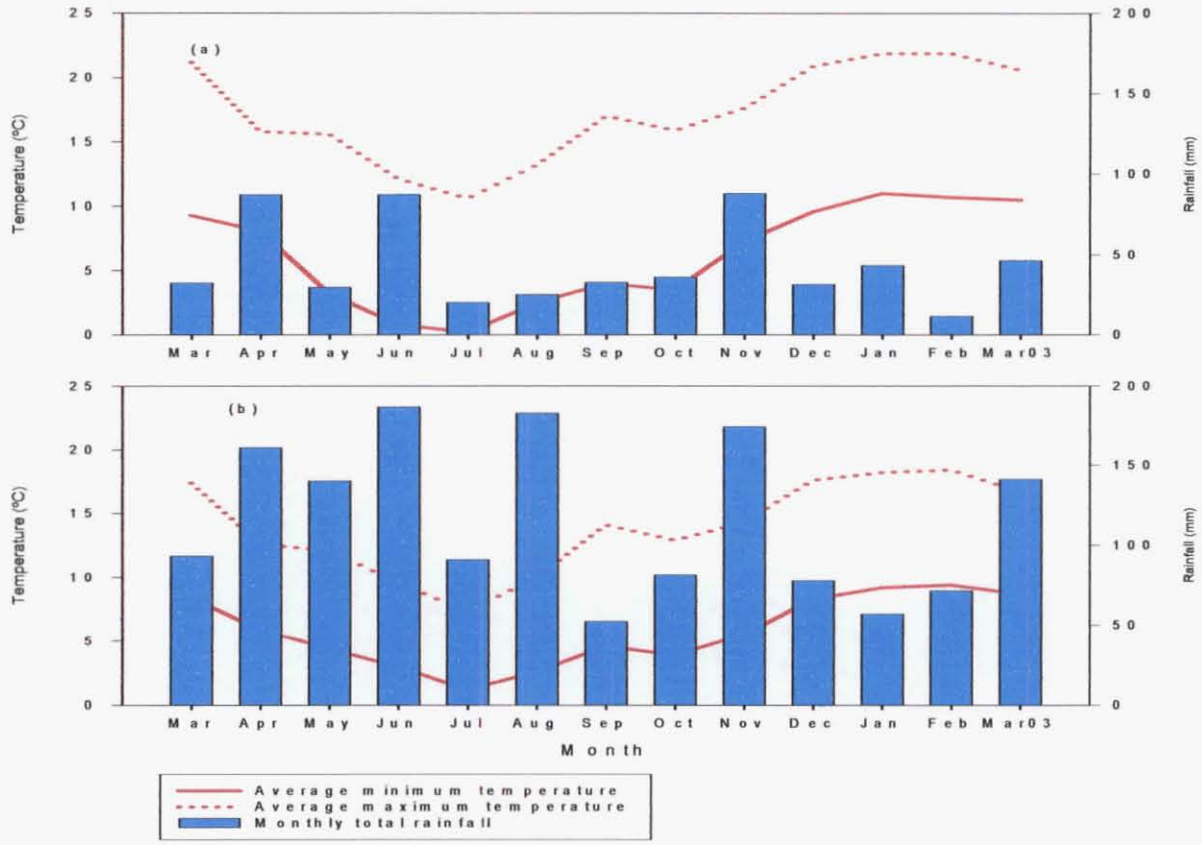


Figure 4.1: The average monthly minimum and maximum temperatures and monthly total rainfall from March 2002 to March 2003. (a) McLeans Island (b) Hinewai Reserve.

Figure 4.2 shows the mean number of gorse pod moths recovered from the pheromone traps during the period of the study at the two sites. Appendix 8 shows the individual numbers of moths trapped.

The 5% LSD calculated for repeated measures ANOVA for the Date × Site was 1.314. This was used to ascertain whether there were significant differences between the two sites for each date shown (Appendix 7). There was a significant difference ($P < 0.05$) between McLeans Island and Hinewai Reserve in the number of male moths caught on each occasion from October 2002 to the end of February 2003 with the exception of 3 January 2003. There was no significant difference between the two sites during the period 27 March 2002 to 17 September 2002 or during March 2003.

The results show that at McLeans Island there were two definite moth generations, peaking in November 2002 and again in February 2003. At Hinewai there was less evidence of a second generation and *C. succedana* was later in becoming active in the spring.

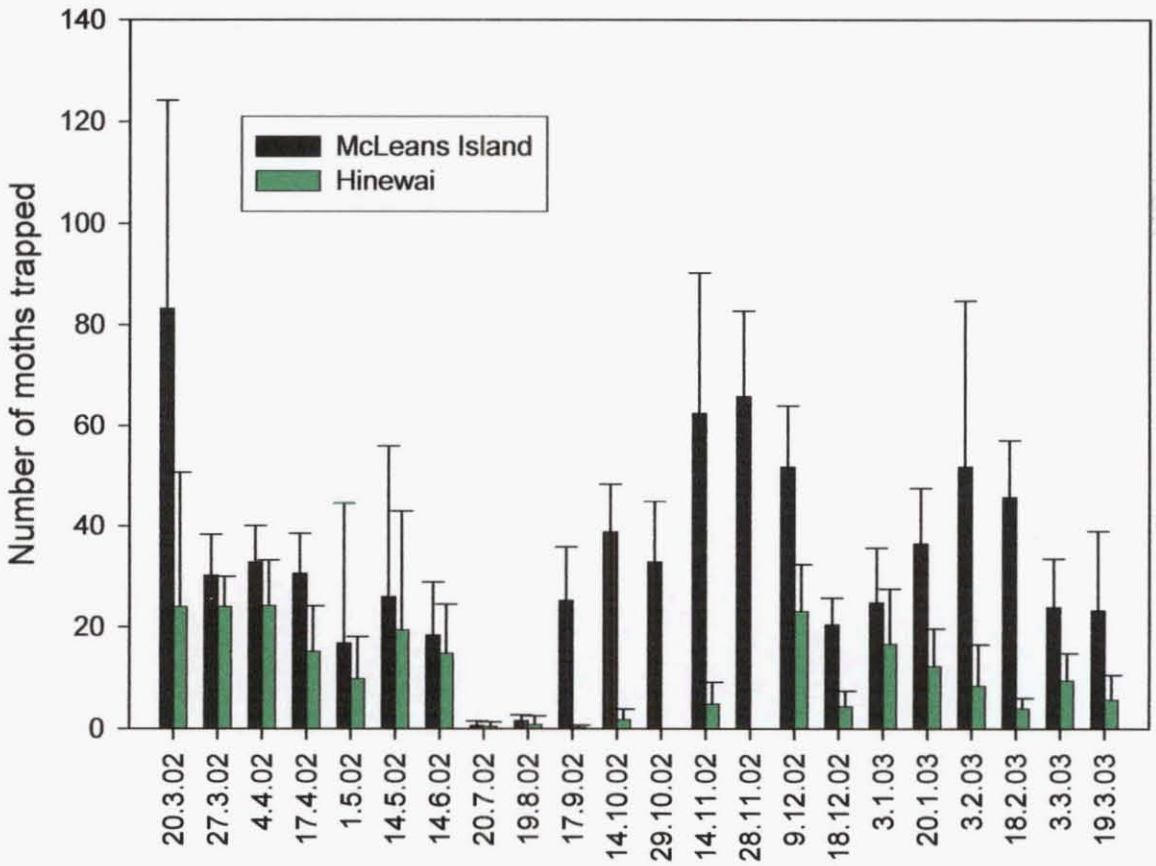


Figure 4.2: The number of male gorse pod moths recovered from pheromone traps from March 2002 to March 2003 at Hinewai Reserve and McLeans Island. I = SE.

4.4 Discussion

The purpose of this experiment was to study the phenology of *C. succedana* with the phenology of gorse. This would assist in assessing the effectiveness of *C. succedana* in assisting in the control of gorse seed production. There has been much research on other members of the genus *Cydia* and these results will be used

for comparison as for such effects as temperature (Chapter 3) but most of it has been for pest species such as *C. pomonella* (codling moth) and *C. nigricana* (pea moth).

In this study, there was a marked difference between the sites in both the rainfall and the minimum and maximum daily temperatures (Figure 4.1). Hinewai Reserve has a cool, wet climate whereas McLeans Island has a dry, warm climate. There was a corresponding difference in the number of male moths trapped (Figure 4.2), which suggests that *C. succedana* activity, like *C. pomonella*, is influenced by temperature.

Although Hinewai Reserve had a warmer monthly average minimum temperature from May to October, the monthly average maxima were lower and it is the daily maximum temperature that effectively governs the development of the moth. At Hinewai, there were individual days where the minimum temperature was several degrees below 0°C with snow on the ground. McLeans Island also had individual days when the minimum temperature was below 0°C. However, when this occurred, the maximum rose considerably (see Appendix 5). This indicates that the gorse pod moth is better suited to a warmer area. This is supported by the results from the pheromone traps, where the number of male moths was always higher at the drier, warmer sample site.

Moths were active throughout the winter at McLeans Island but there was less activity at Hinewai Reserve during the same period. *Cydia succedana* became active at McLeans Island in September, when the monthly average maximum temperature was 17°C. Hinewai Reserve moths showed little activity until November (average maximum temperature 14.3°C) and moth activity did not peak there until January and appeared to be peaking again in March 2003.

The different phenology stages of the gorse plants were also noted at the two pheromone trap sites. At McLeans Island, the gorse had a high percentage (estimated > 75%) of flowers in September and the remaining portion had buds about to burst into flower. Hinewai Reserve did not have the same proportion of flowers until October. There was a small percentage (20%) of green gorse pods showing in November at McLeans Island and a smaller percentage present at Hinewai Reserve. At McLeans Island, there were no blackened gorse pods produced due to several other biological control agents being present, e.g., *Anisoplaca ptyoptera*. At Hinewai Reserve the first blackened pods did not appear until January and the main

production of mature pods (> 50%) did not show until February - March 2003. At McLeans Island, there was a second generation of buds and flowers present during February and March 2003.

The first pheromone trap sample had considerably more moths than any other occasion at McLeans Island. This may have been caused by two factors. The first factor was that the McLeans Island had a two day longer period between establishment and first count than Hinewai Reserve (6 March to 20 March v 8 March to 20 March). This means that there was a chance to trap more moths. After the first base had been changed, there was no significant difference between the two sites during the autumn/winter months. The second factor was that many moths were already flying around the McLeans Island area when the pheromone traps were set out on 6 March 2002. Therefore, the catch would have some older, already emerged males as well as those that emerged between 6 and 20 March. Catches after 20 March are better indicators of moths emerging during the sample period. Since pheromone traps attract only male moths, there may have been an effect on the number of females that were mated, which in turn may affect the number of fertilised eggs laid. The pheromone bait may also attract male moths from a greater distance than the normal flight range of male moths.

As discussed in the literature review, development of species of the genus *Cydia* is governed by environmental temperature (Rock and Shaffer, 1983), and is measured more precisely by physiological time (degree-hours or degree-days) than by calendar time (days) (Taylor, 1981).

Cydia succedana phenology appears to be synchronised with the phenology of gorse, especially for the first generation at both sites. However, there was less synchronicity for the second generation. This was particularly noticeable at McLeans Island where there was a definite second peak of *C. succedana*. At Hinewai Reserve, where there was only one reproductive period of gorse but there appeared to be two generations of *C. succedana*.

4.5 Conclusions

The results of this study support the findings of Suckling *et al.* (1999) in that the phenology of *C. succedana* is synchronised with the phenology of *U. europaeus*

for the first generation of *C. succedana*. There does not seem to be such good synchrony in the second generation in the Canterbury region.

There was a significant difference in the number of male moths recovered between the two sites from October 2002 to February 2003. More male moths were caught at McLeans Island. This suggests that *C. succedana* is probably better suited to regions that are warmer.

Chapter 5

Measuring the Infestation of Gorse Pods by *Exapion ulicis* and *Cydia succedana*

5.1 Introduction

Gorse (*Ulex europaeus*) has been a noxious weed in New Zealand since 1900 (Moss, 1960). To combat the problem of gorse spread, the concept of biological control of gorse was implemented early. The gorse seed weevil (*Exapion ulicis* (Förster) as *Apion ulicis*) was introduced into Nelson and Alexandra in February 1931 with the aim of destroying gorse seed. It is now widespread and is common in both islands of New Zealand (Kuschel, 1972) (see Section 2.3.3.5).

To gain better control of gorse seed production, the gorse pod moth (*Cydia succedana* (Denis & Schiffermüller)) was introduced into New Zealand in 1992 (Suckling *et al.*, 1999). In Europe, *C. succedana* has two generations per year. Larvae attack *U. europaeus* seed in spring and other *Ulex* species in autumn. Research into host-specificity was completed in 1991 (Hill *et al.*, 1999). The moth is now abundant at the original release sites (Hayes 1999).

The aim of this work was to determine the relative infestation levels by *E. ulicis* and *C. succedana* at various sites in the South Island of New Zealand. While studying the effectiveness of both of these biological control agents, it was possible to observe whether they were complementary or competitive in controlling gorse. From this work it will be possible to determine the percentage of gorse pods that has been damaged by the insects.

5.2 Materials and methods

5.1.1 Sample collecting

Samples of 25 black gorse pods were collected from Bainham, Onekaka, East Takaka, Hinewai, Trotters Gorge and Lake Ohau. The GIS reference and altitudes for each sample site are given in Appendix 1. A location map for all sites is given in Figure 1.2.

5.2.2 Climate

The daily minimum and maximum temperatures and daily rainfall were recorded from March 2002 to March 2003 on site, where possible, for each site. Temperature records for East Takaka and rainfall records for Onekaka were not available so NIWA records for Kotinga were used. Kotinga is approximately 10 km northwest of East Takaka and 30 km southeast of Onekaka. Records for Lake Ohau were taken from Tara Hills (30 km southeast) for temperature and Chain Hills (35 km southeast) for rainfall. Trotters Gorge is approximately equidistant from Oamaru (35 south km) and Palmerston (33 km north); therefore, both sites are included in the graphs. At Hinewai Reserve there were rainfall and minimum and maximum temperature recording facilities close to the experimental site (Appendices 2 & 3).

5.2.3 Plant activity

The phenological stage (buds, flowers, green pods and black pods) of the gorse plants was estimated at each visit to the sites. Observations were made monthly and the minimum interval recorded was 5%. If the estimate was below 5%, the condition was recorded as zero. No pods were produced at McLeans Island over the 13 months of monitoring due to the gorse being attacked by several biological control agents as shown in Plate 5.1. Plate 5.2 shows gorse in full flower, Plate 5.3 shows green pods and Plate 5.4 gives an example of ripening pods. The monthly estimates of the individual sample plant's activities are given in Appendix 9.

The number of damaged pods and the total number of undamaged seeds was recorded. Damaged pods were separated into pods damaged by the gorse pod moth and pods damaged by the gorse seed weevil. Few pods were attacked by both agents. The gorse pod moth was active for a prolonged period, whereas the gorse seed weevil was active for only 2 - 3 months. Appendix 10 shows the percentage of sample pods that were damaged by *E. ulicis* and *C. succedana*.

Plate 5.1: Gorse bush at McLeans Island, showing results of attack by several biological agents.

Plate 5.2: Example of a gorse bush in full flower.

Plate 5.3: Example of green pods on a gorse bush.

Plate 5.4: Example of ripening gorse pods.

5.2.4 Data collection and statistical analysis

Data were analysed using the arc sine transformation of percentage for analysis of variance with the SYSTAT 9 package and graphs were drawn using the Sigma Plot 2001 package. To compare results at the different sites, two analyses were done. The first was between the Golden Bay sites over the whole experiment because the sites from Golden Bay had seed pods on them for most of the year. The second analysis was a comparison between all the sites over the summer when seed pods were produced, which was when the gorse seed weevil was also present.

5.3 Results

The gorse plants were at different heights when compared site-to-site (Appendix 11). The differences may have been due to different ages but this was not measured. Alternatively, the differences may have been caused by nutrient deficiency of one or more nutrients, or by climatic differences. Along with different heights, there were differences in the number of seeds produced.

A direct count of the number of seeds the gorse pod moth had attacked could not be ascertained because moth larvae, when present, completely destroyed all of the seed in the pods. However, by calculating the average number of seeds in undamaged pods and multiplying this figure by the number of damaged pods gave an estimate of the number of seeds that were damaged each month. These estimates are shown in Table 5.1 for *Cydia succedana* and in Table 5.2 for *Exapion ulicis*.

The results showed that gorse produced ripened pods almost continuously in Golden Bay but in the southern regions pods were produced only in the spring; the difference being due to climatic differences (Appendices 2 & 3). The results also showed that the best percentage of pods damaged by *C. succedana* was 45% and the best percentage of pods damaged by *E. ulicis* was 76% (Appendix 10).

The climatic conditions also affected the *C. succedana* activity. As was shown in Chapter 4, *C. succedana* activity depended on temperatures to stop and start activity. At McLeans Island, *C. succedana* was active until July when the monthly average maximum and minimum temperatures were 10.6°C and 0.2°C. Activity started again during September (monthly mean maximum and minimum temperatures, 17.0°C and 4.0°C). At Hinewai, moth activity ceased during July

(minimum and maximum monthly temperature average, 7.3°C and 1.2°C) and did not resume until November (monthly mean temperatures, 14.3°C and 5.5°C).

Table 5.1: Estimated number of gorse seeds damaged per 25-pod sample by *Cydia succedana* at the various sample sites and times.

Site	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Bainham	17.9	20.1	7.1	6.5	-	3.9	8.6	12.7	23.0	3.8	-
Onekaka	39.2	10.0	6.4	5.7	3.8	-	11.4	6.5	3.4	-	-
East Takaka	69.8	7.4	5.9	5.7	3.7	0.6	8.7	8.8	3.8	-	-
Hinewai	-	-	-	-	-	-	-	-	4.2	22.2	31.3
Trotters Gorge	-	-	-	-	-	-	-	-	7.7	5.7	3.1
Lake Ohau	-	-	-	-	-	-	-	2.8	15.1	-	-

Table 5.2: Estimated number of gorse seeds damaged per 25-pod sample by *Exapion ulicis* at the various sample sites and times.

Site	November	December	January	February	March
Bainham	4.3	10.0	13.4	-	-
Onekaka	10.5	18.1	8.8	-	-
East Takaka	13.8	12.6	7.8	-	-
Hinewai	-	-	9.8	11.6	18.1
Trotters Gorge	-	-	28.7	15.9	15.6
Lake Ohau	-	39.4	30.4	-	-

The main climatic factor appeared to be temperature since there was gorse growing well in low rainfall areas as well as in high rainfall areas. However, in the low rainfall areas (McLeans Island and Lake Ohau) the gorse was stunted compared with plants in high rainfall areas (e.g., Bainham). At McLeans Island, the plants were less than one metre tall, whereas at Bainham and Hinewai the plants were in excess of three metres tall (Appendix 11). It was not known how old any of the gorse plants were, which may explain some of the height difference.

Climatic records for each of the sites show that there was a marked difference in the rainfall and maximum and minimum temperatures among the sites, both during 2002-3 and where records have been kept previously. The minimum and maximum daily temperatures and the rainfall for each site during the period of the experiment are shown in Appendices 2 and 3 and a comparison can be made with the average annual rainfall (Table 1.2).

During the winter of 2002, mild conditions prevailed in Golden Bay. There were no frosts in Bainham until July (Ross Haldane, pers. comm.), whereas in previous years severe frosts have occurred as early as March and there are normally severe frosts in April.

As a consequence of the mild conditions, there were gorse flowers and pods produced at all the sites in Golden Bay throughout the winter (Appendix 9). Further south there was no production of flowers or seed during the autumn - winter period. The climatic conditions affected the plant activity. At Lake Ohau, the gorse did not flower until September – October with some flowers in November. There was a high percentage of sample plants showing green pods in November. Brown pods were present during December and January, although not many pods were present in January. The seasonality of the gorse plant reproductivity followed a similar pattern at Trotters Gorge and Hinewai, although there seemed to be a longer period for the latter two.

Although there were climate differences among the sites, there was no significant difference in the proportion of gorse pods damaged by the gorse pod moth ($P = 0.574$). However, there was a significant difference among times ($P < 0.001$), which reflects the seasonality of *C. succedana* and the gorse. The site by time interaction was not significant ($P = 0.073$), although the results were almost significant. Figure 5.1a shows the percentage of gorse seed pods that were damaged by *E. ulicis* at the three Golden Bay sites and Figure 5.1b shows the estimated percentage of gorse pods damaged by *C. succedana* in Golden Bay. Monthly average maximum and minimum temperatures and the monthly rainfall for all six sites over the study period are shown in Figure 5.2a – g. Daily records are shown in Appendices 2 and 3. In the south, where the insects were active for a shorter period, there was a shorter time where the monthly average maximum temperature was above 10°C.

The monthly average maximum and minimum temperatures and monthly total rainfall for the three Golden Bay sites are shown in Figure 5.2a - c. There were marked differences among sites in both rainfall and maximum and minimum daily temperatures. Bainham had a wet and cool year, while East Takaka had a dry warm year. Onekaka had a total rainfall between that of Bainham and East Takaka. Long-term records show that this is normal. Temperatures at Onekaka were also between those of Bainham and Takaka during the study. There were no temperature records for Bainham during January 2003, due to absence of the record keeper.

Figure 5.3 shows the mean percentage of gorse pods that were damaged by either the gorse pod moth or the gorse seed weevil and the individual sample percentages are shown in Appendix 10.

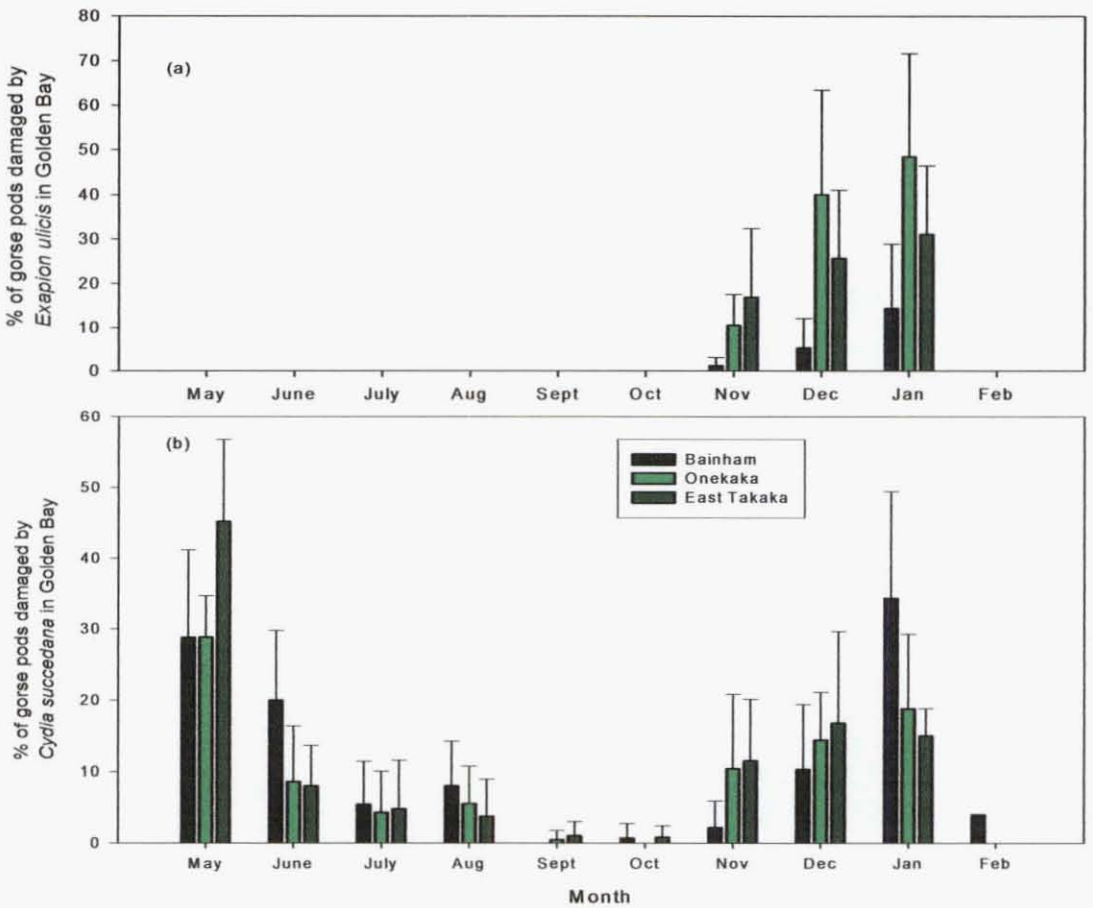
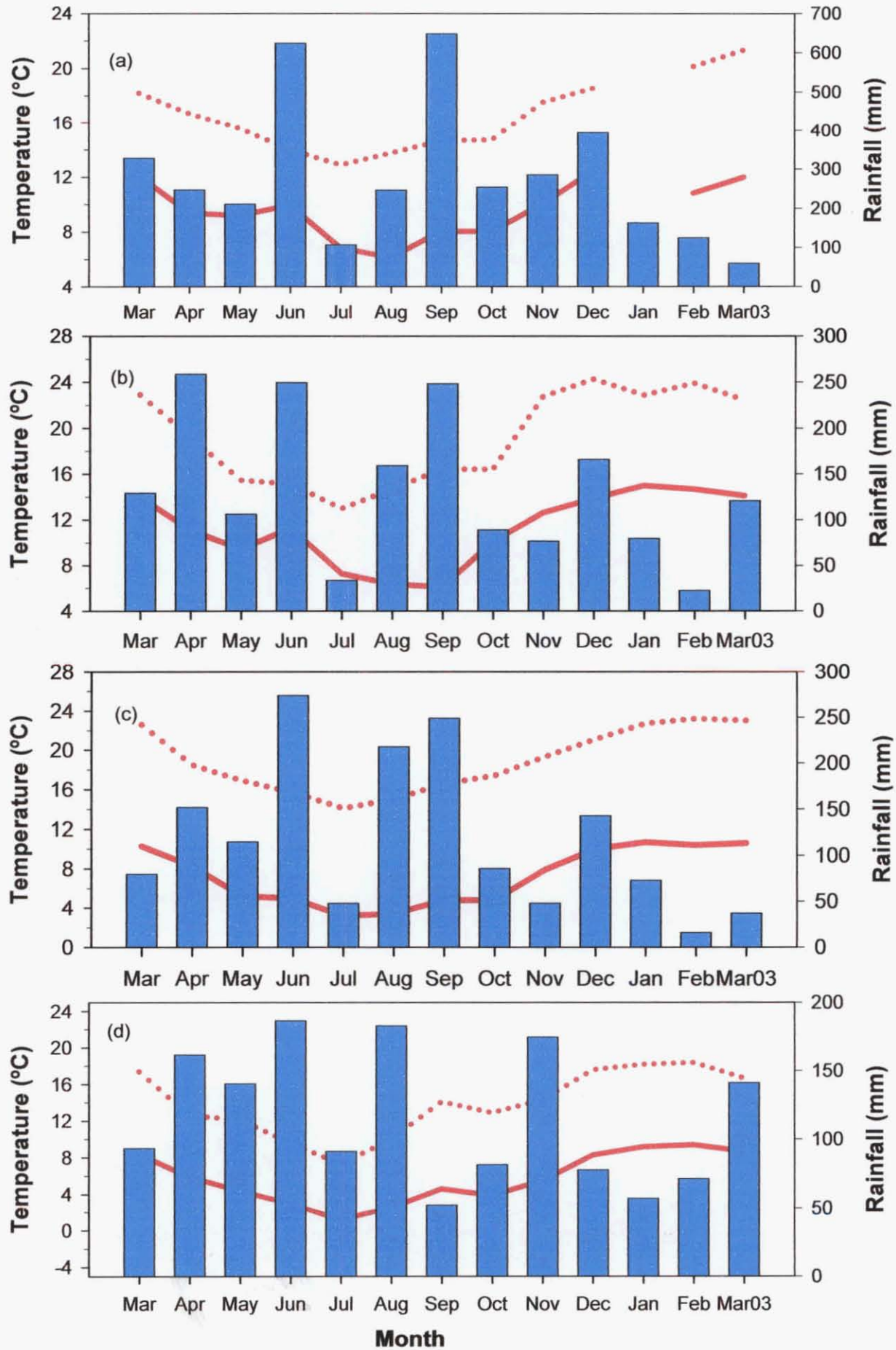


Figure 5.1: Percentage of gorse pods damaged by insects at Golden Bay during the summer months. a) *Exapion ulicis,* b) *Cydia succedana.* I = SE.


(a)
(b)
(c)
(d)
Temperature (°C)
Rainfall (mm)
Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar03
Month

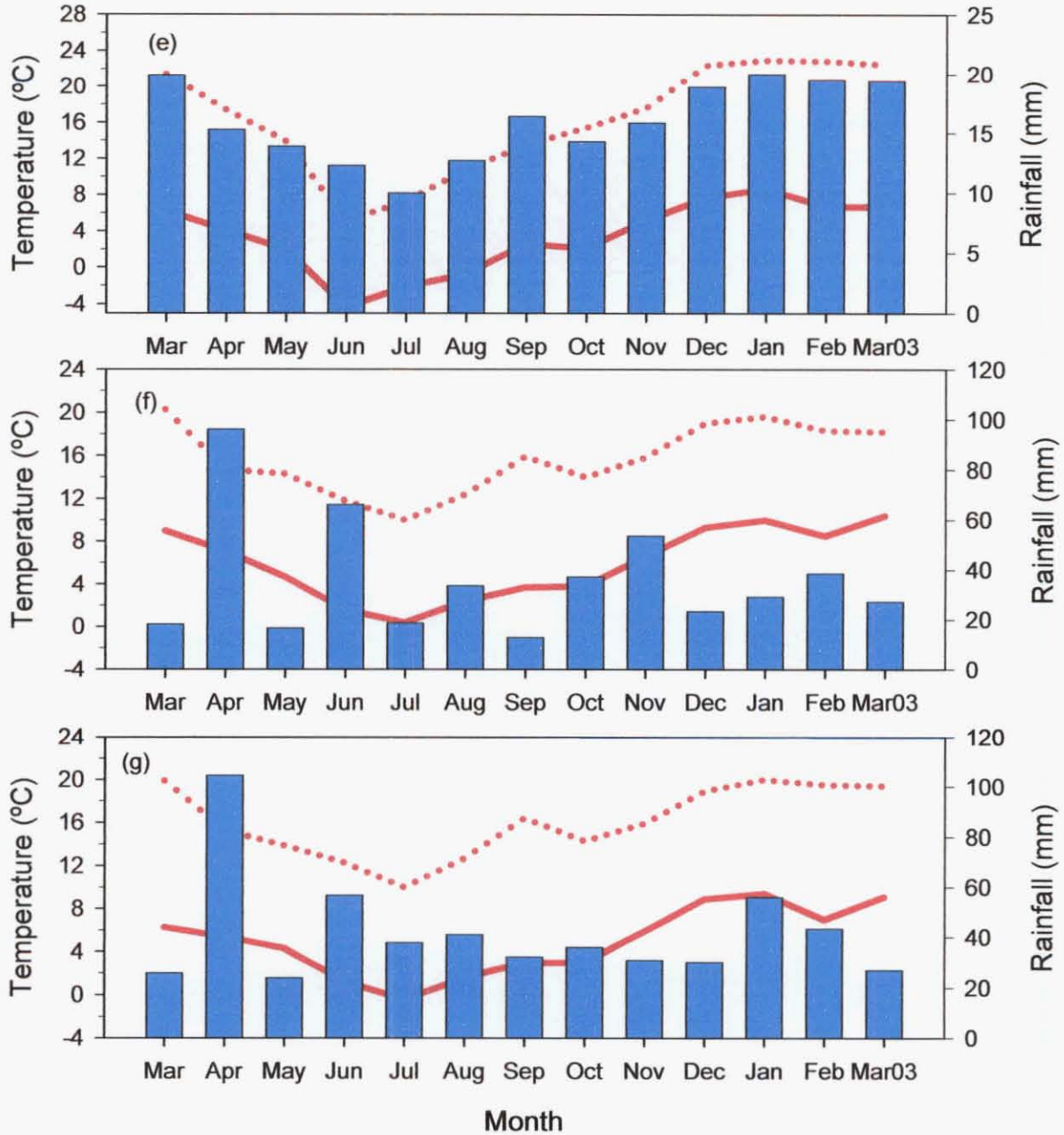


Figure 5.2: Average maximum and minimum temperatures and monthly total rainfall for each of the experimental sites. (a) Bainham, (b) Onekaka, (c) East Takaka, (d) Hinewai, (e) Lake Ohau, (f) Oamaru, (g) Palmerston.

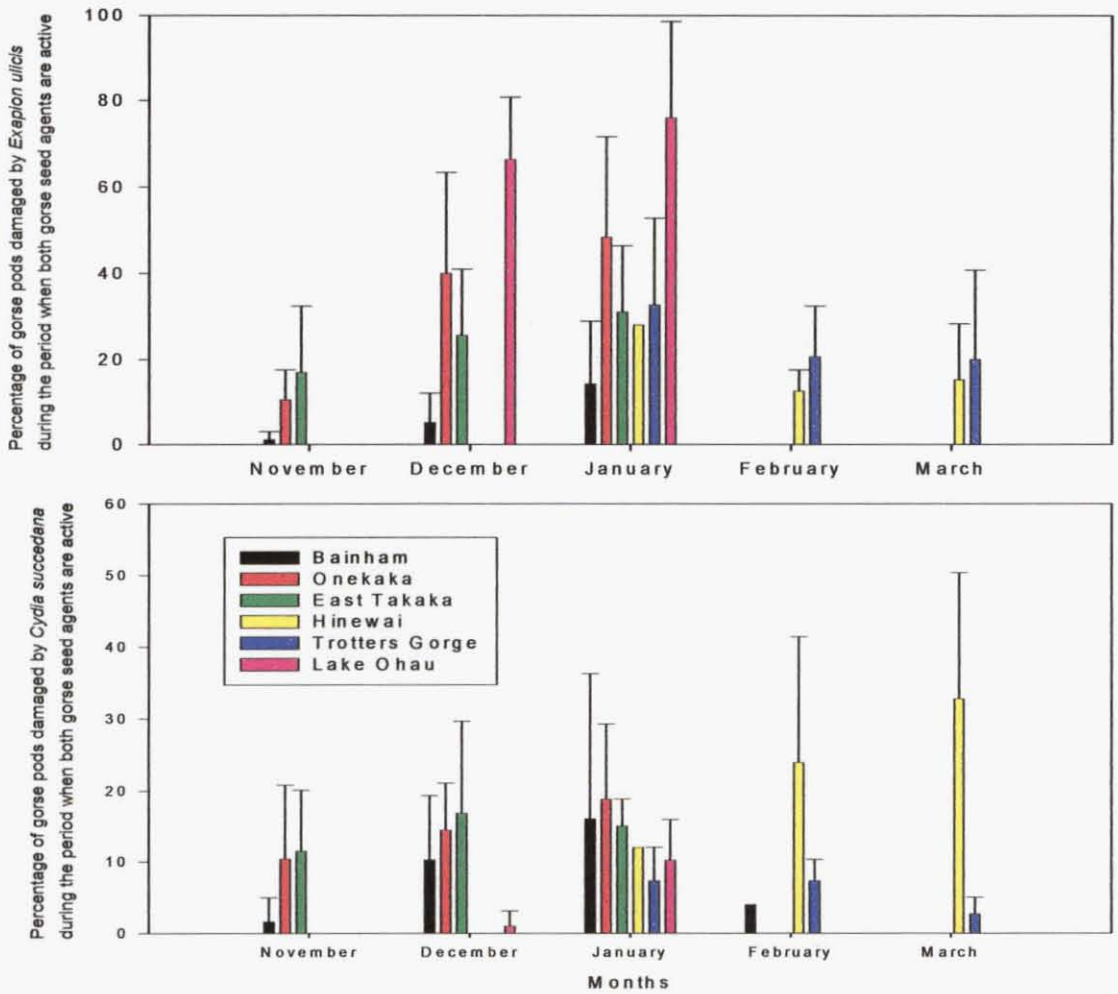


Figure 5.3: Mean percentage of gorse pods damaged at all of the sites during the summer period (November – March) by a) *Exapion ulicis* or b) *Cydia succedana*. I = SE

5.4 Discussion

The purpose of these studies was threefold: first to confirm whether *Cydia succedana* had established itself at various sites in the South Island of New Zealand. Second, to ascertain the proportion of gorse pods that were damaged by *C. succedana*. Third, to determine the percentage of gorse pods that were damaged by the two gorse seed feeders, *C. succedana* and *E. ulicis*, when they were both active. This would assist in ascertaining whether these two biological control agents were

complementary or competitive in their control of gorse seed production. This information could then be used to decide whether it was necessary to introduce further gorse seed feeding biological control agents into New Zealand.

Cydia succedana was released in Golden Bay in 1993. In the southern regions, *C. succedana* was initially released on the Banks Peninsula in 1992. There have been subsequent releases. The Mackenzie Basin saw releases in 1995-96. There have been no releases at Trotters Gorge but there have been several releases at the nearby Mt Herbert Forest (1992, 1994, 1995) (A.H. Gourlay, pers. comm.). *Cydia succedana* has now been released for a sufficiently long period to become well established. However, it appears that the extreme winter cold in these southern regions may have hindered the insect's establishment and spread.

Cydia succedana damaged a high percentage of gorse pods sampled from Golden Bay (Figure 5.1b). However, it is very seasonal and it appears that the two periods when the most pod damage pods occurred were May 2002 and December 2002 - January 2003. This coincided with the main periods of gorse seed pod production of April 2002 and November 2002. From this work it appears that the autumn generation of *C. succedana* had a greater impact on the basis of the percentage of infested pods.

Cydia succedana has better phenological synchronicity with gorse than *E. ulicis*, especially in Golden Bay. This conclusion is supported by the estimated number of gorse seeds consumed (Table 5.1). These estimates show that the greatest activity of the gorse pod moth was in May 2002. Bainham was wetter and cooler (Fig. 5.2), which may explain why less gorse seed was damaged there. However, the estimated seed consumption at Bainham was higher in June, which supports the presumed temperature effect. December 2002 and January 2003 saw higher estimated seed consumption at Bainham. The estimated consumption was very similar to that in the previous May and June. Onekaka and East Takaka consumption estimates for summer were not markedly higher than the estimates for June to October.

Cydia succedana has two generations a year in Europe and it appears that this also occurs at Golden Bay and the generations are in synchrony with the production of gorse pods. Suckling *et al.* (1999) found that in Darfield, Canterbury, there was a lack of synchrony between the insect and the weed in the second burst of seed production.

In March 2003, gorse plants in Golden Bay were in bud and were flowering with some green pods. This occurred despite a severe summer drought. The summer rainfall was lower than normal over December 2002 to February 2003 (Bainham, 683 mm; Onekaka, 268 mm; East Takaka, 132 mm) (Appendix 2). The reproductive activity of gorse in Golden Bay during March 2003 may have been because of the plant's reaction to the stress of a drought.

When sampled in April 2002, gorse plants in Golden Bay were flowering and had green pods. *Cydia succedana* eggs would have been laid in April for the high percentage of sampled pods that were damaged in May. By May, the gorse bushes had approximately 40% black pods, approximately 40% green pods and there were still some flowers (20%). By June there were more black pods (60%), with 30% green pods and approximately 10% flowers. There were no significant differences among the three Golden Bay sites within each month, although there were significant differences between months.

During November – March, both control agents were active in Golden Bay and in the southern regions. There were significant differences among sites and months. The results show that *C. succedana* is more effective for longer in warm regions. However, in February and March 2003, there was a high percentage of gorse pods damaged by *C. succedana* at the cooler Hinewai Reserve. The monthly average maximum temperature for Hinewai in March 2003 was 17°C.

Exapion ulicis appeared to damage a higher proportion of seed than *C. succedana* in the southern region. This was probably due to the fact that there were relatively few *C. succedana* moths present. This suggests that *E. ulicis* may be better adapted to colder temperatures than *C. succedana* but it may simply reflect the fact that *C. succedana* has not had sufficient time to build up its population in the south because of the lower temperatures.

The estimated number of seeds damaged per sample by *E. ulicis* (Table 5.2) show that at Lake Ohau the number of gorse seeds that were damaged was up to 30.4, whereas the estimate for *C. succedana* was only 15.1 seeds per 25 pods sampled. At Hinewai and Trotters Gorge, the estimates were not quite as high for *E. ulicis* (up to 28.7 seeds damaged). The estimates suggest that considerably less gorse seed damage by *C. succedana* is likely to occur at Trotters Gorge than at Hinewai (16.5 v 57.2 seeds damaged). Golden Bay sites had less estimated gorse seed damaged by *E. ulicis* than *C. succedana* at Bainham and Onekaka during November.

The estimates showed that *E. ulicis* was predominant at Onekaka and East Takaka during December and January but at Bainham *C. succedana* damaged more gorse seed. The various sites had different emergence times for *E. ulicis* and *C. succedana* due to the climatic conditions that also caused different times for the phenology of the gorse plants.

There has been little research on the effectiveness of *E. ulicis* in New Zealand nationwide. Previous research has all been conducted near Auckland (Cowley, 1983; Hoddle, 1991). They found that the weevil reduced the number of viable seeds from approximately three-seeds/pod to one-seed/four pods. These studies, as well as a study in Canterbury (Hill *et al.*, 1991a), found that *E. ulicis* could damage a high percentage of the spring pods but did not attack autumn-produced seed.

The results from Golden Bay showed that during the months that both insects were active, November - January, 40% of gorse pods were damaged by the insects. However, over the entire study period only 20% of pods were damaged. Gorse plants produce many seed pods each reproductive season and up to 80% of the undamaged seed produced can be viable (Sixtus *et al.*, 2003a) (Appendix 5). In addition, weevil damaged gorse seed, that is only lightly damaged, can still germinate (25%) (Sixtus *et al.*, 2003b) (Appendix 6).

With a high seedling survival rate, seed feeders would have very little impact on gorse abundance. However, if seedling survival is low, seed feeders can have a dramatic impact on the abundance of gorse. In models for broom (*Cytisus scoparius*), Rees and Paynter (1997) found that there was an interaction between the disturbance regime and the impact of biological control agents. At high levels of disturbance, young pre-reproductive plants dominate the gorse population, reducing the seed population as very few plants produce seed. Under these conditions seed feeders have their greatest impact (Rees and Hill, 2001).

Ivens (1978) found that the annual gorse seed fall was 500 – 600 seed/m^2 at Palmerston North. Estimated numbers from individual collecting trays varied from 180 – 950 seed/m^2 in the first year and 170 – 1,620 seed/m^2 in the second year. However, in Golden Bay, though there were not as many seeds on the trays, the counts of good seed in the samples showed that there was a high seed production (up to 560 seed/sampled bush). Sites further south producing only 15 - 55 undamaged seed/plant/year.

The southern sites produced seed only in the spring. Thus seed-producing plants could have experienced increased attack from both *E. ulicis* and *C. succedana*, providing that the insect emergence was synchronised with gorse seed production. At Lake Ohau, a high percentage of gorse seed was damaged by *E. ulicis* (approximately 76%) over the two months that the gorse plants were producing blackened pods. *Cydia succedana* damaged less than 10% of pods during the same period. This may reflect the inability of *C. succedana* to adapt to the extreme winter cold in this region or it may be due to a low population that is still building up but only slowly. These results indicate that either the southern region's temperatures are too low for survival or that the insect has not migrated to the area in numbers large enough to have a significant impact on gorse seed production. The results from these sites indicate that much gorse seed escapes predation by both of these insect species even though there is only one gorse seed production period each year.

At Hinewai Reserve and Trotters Gorge, both *E. ulicis* and *C. succedana* were active from January to March. However, *C. succedana* damaged fewer than 10% of the pods while it was active at Trotters Gorge. At Hinewai Reserve, most damage occurred in March when 30% of pods were damaged. *Exapion ulicis* damaged approximately 20% of pods at both Hinewai Reserve and Trotters Gorge.

Previous studies have shown that *C. succedana* larvae consume *E. ulicis* larvae encountered in pods (Hill and Gourlay, 2002). However, in an earlier study of gorse seed predation in England, fewer than 20% of *U. europaeus* pods occupied by insects contained both species (Hill, 1982). In the fieldwork of this study, less than 5% of sampled pods contained both insects. However, there were several pod samples where *C. succedana* larvae were present, or had been present, but there was no trace of *E. ulicis*, when there were *E. ulicis* larvae present in other pods. Therefore *E. ulicis* larvae may have been consumed earlier. Another aspect of competition is that there are plenty of pods available; therefore, any competition between the larvae of the seed-feeders is likely to be low. The competition between the seed-feeders would intensify only when the percentage of pods infested increased. Further research is required to confirm if *C. succedana* larvae are consuming any *E. ulicis* larvae.

5.5 Conclusions

From these results, it appears that the climate in Golden Bay is suited to *C. succedana* as a gorse seed production-control insect whereas in the more southern regions of the South Island it may not be so well suited because of the colder climate. *E. ulicis* seems to be better suited to the colder climate. The percentage of gorse seed pods damaged by both agents varied from month to month. *Cydia succedana* had a longer active season, especially in Golden Bay and, overall, it damaged approximately 20% of gorse pods.

There is some evidence that the two biological agents are in competition, but further research is required to ascertain if *C. succedana larvae* consume *E. ulicis* larvae. This is only one aspect of competition. The second is that there are plenty of pods available; therefore, any competition between the seed-feeders is likely to be low. When all pods are infested the competition would intensify. In addition, it will be necessary to ascertain the percentage of *E. ulicis* larvae consumed by *C. succedana* larvae.

Chapter 6

Gorse seed viability

6.1 Introduction

As indicated previously, gorse (*Ulex europaeus* L.) was introduced into the New Zealand as an inexpensive, quick-growing hedge for stock containment and shelter (Moss, 1960). However, it soon became a weed and was declared a noxious weed in 1900 (Cowley, 1983). Due to the favourable climate for its growth in much of New Zealand, gorse has two reproductive cycles a year, one in spring and the other in autumn. Gorse is a prolific seeder and the seed is viable for at least 40 years (Zabiewicz 1976; Zabkiewicz and Gaskin, 1978). The ability of gorse seed to remain viable for many years, requiring only to be brought nearer to the soil surface for germination to occur, means that the weed can rapidly re-establish gorse infestations (Ivens, 1982).

Markin and Yoshioka (1996) studied the phenology of gorse in Hawaii (Chapter 2). There is no literature on gorse phenology and pod growth rates for New Zealand, but it can be assumed that it would be very similar to that of Hawaii.

The aim of this study was to compare gorse seed fall at different sites in the South Island of New Zealand to see if gorse in the colder regions, which reproduces only once per season, had a different level of viable production than that produced in warmer areas. Gorse produces many seed but it is not known what proportion of that seed production is hard or dead and the purpose of this study was to determine these amounts. In addition, seed from sampled pods was also tested for its viability.

6.2 Materials and Methods

6.2.1 Sample Sites

Gorse seed was collected from six locations in the South Island of New Zealand. The sites are the same as those detailed in Chapter 5 (Appendix 1).

6.2.2 Seed sampling

Seed trays were placed under randomly selected gorse bushes. Bushes were selected using a 1-20 random numbers table. The sample sites were selected by pacing the random numbers from sample bush to sample bush. Seed fall from sampled bushes was collected in circular seed trays of 24.5 cm diameter (1,481 cm^2). The number of seeds/m^2 was calculated by multiplying the number of seeds collected in a tray by 6.75. Fallen seed was collected monthly, when plant activity was inspected.

When the pods were black, a sample of 25 pods wad taken from each sample bush. The number of undamaged seeds was counted, and the number of damaged pods recorded (Appendix 10). Seed was stored at 4°C until required for germination testing. When tested for viability, both fallen seed and seed from the pod samples were tested.

6.2.3 Sterilisation

For germination tests, all equipment used was sterilised in an autoclave and only sterilised water was used. To minimise the risk of infestation by fungi and bacteria, seed samples were washed in 2.5% sodium hypochlorite (NaOCl) for 5 min. The seed was then rinsed and air-dried overnight at room temperature.

6.2.4 Acid scarification

A previous experiment (Sixtus *et al.*, 2003a) to find the best scarification method for gorse seed showed that scarification with concentrated sulphuric acid (H_2SO_4) (36N) for 180 min gave the highest seed germination. The same experiment also tested optimum germination temperature. The results showed that the best gorse seed germination temperature was 15°C (Appendix 3).

Two volumes of acid to one volume of seed were used (Hartmann *et al.*, 2002). Seed samples were placed in the concentrated sulphuric acid (36N) for 180 min. Following acid treatment, seeds were washed in running water until the pH was neutral and then the seeds were rinsed in sterile water. After rinsing, the seeds were placed in Petri dishes. All seed from the seed fall was placed in a dish regardless of the number of seeds. For the pod samples, there were 25 seeds/dish.

6.2.5 Germination temperature

The germination cabinet temperature was kept at a constant 15°C with a 16 h light and 8 h dark cycle. The seeds were placed on moist germination paper in a Petri dish. Seed was germinated for 10 days. Dishes were inspected daily and sterilised water added as required.

6.2.6 Data collection and statistical analysis

The number of seeds germinated was counted 10 days after scarification. A seed was counted as germinated when it showed a radicle that was at least the length of the seed. Seedlings were not classified as normal and abnormal.

Data were analysed with analysis of variance using the SYSTAT 9 package. Graphs were drawn using SigmaPlot 2001.

6.3 Results

6.3.1 Climate

The daily minimum and maximum temperature and daily rainfall were recorded from March 2002 to March 2003 on site at each site, (Chapter 5). The climate data are shown in Figure 5.2a - g. The monthly rainfall and average minimum and maximum temperatures for the 13 months of the experiment are shown and the daily records are in Appendices 2 & 3. The average yearly total rainfall is given in Table 1.1.

The field results showed that gorse produced ripe seed pods almost continuously in the Golden Bay region. However, in the southern regions it was limited to spring seed production. At McLeans Island no pods were produced to the blackened stage over the 13 months of the experiment due to attack by several biological control agents. Therefore, there are no results for McLeans Island.

6.3.2 Comparison of results

To compare results among sites, three studies were completed on sampled gorse seeds. The first was between the seed fall samples that had fallen into the seed tray. The number of seeds that fell into the seed trays was converted to the number of seeds/m^2 (Appendix 4). This study was completed over the whole experiment, when there were seeds in the seed trays. Plate 6.1 shows a seed tray with gorse seed present. Unfortunately, seeds were not collected from all the seed trays; the Lake Ohau site did not have any seed fall into the trays.

Figure 6.1 shows the percentage of the gorse seed that germinated both from the seed fall and sampled pods during the 13 months that the six sites were sampled. The seed viability was also tested. Due to the different numbers of seeds in each sample that was germination tested, the final results were converted into percentage viability (Figure 6.1a).

The second study was among all sites over the summer (November 2002 – March 2003). This was a comparison among the six sites of the viability of seed from the sampled pods (Figure 6.1b). The third study at the Golden Bay sites was with sampled pods taken over the whole study (Figure 6.1c). The viability for the individual seed samples is shown in Appendix 4.

The results for the seed fall tests showed significant differences in the monthly seed fall germination ($P < 0.009$). The results showed a tendency for some month × site interaction. There was no difference among sites. Where there was no seed fall, samples were excluded from the analysis of the results.

Comparing all six sites over the summer showed that there was a difference between the Golden Bay sites and the southern sites. The southern sites had considerably less viable seed. The Golden Bay pod seed samples showed a significant difference among sites ($P < 0.05$) but month to month there was no significant difference ($P = 0.349$).

6.4 Discussion

The purpose of this study was to ascertain the effect of climatic conditions on the annual gorse seed fall. The viability of the fallen gorse seed was tested and as a comparison, the viability of the seed sampled from gorse pods was tested over the

same period. Comparisons among sites were used to ascertain whether or not seed viability differed in the different areas.

The total number of seeds caught in the seed trays for each sample varied from 0 - 304 seed/m^2. Ivens (1978) found that at Palmerston North, annual gorse seed fall was 500 – 600 seed/m^2. Individual totals varied from 180 – 950 seed/m^2 in the first year and in the second year the variation was 170 - 1620 seed/m^2. In his study seed trays were arranged in groups of four. In this study there was only one seed tray under each sample bush. This may have reduced the number of seeds that fell into the seed trays due to variation in seed fall due to pod shatter at maturity.

There was a marked difference among the sites in the annual seed production, as well as the length of the reproductive phase of the plants. The Golden Bay sites were reproductive almost continuously, with production peaks occurring in June 2002 and in December – January 2002-03. The southern sites had only one reproductive phase, during spring-summer. This is probably because of the harsh winter conditions in the southern regions. Figure 5.2 shows that the average monthly minimum temperatures during the winter months, the southern regions were below 0°C and or close to 0°C. In Golden Bay, the average monthly minimum temperatures were considerably higher (approximately 5°C) and this could assist a longer reproductive phase per season. While the minimum temperature average in Golden Bay was 5°C, this was still below the minimum temperatures outlined in Chapters 4 and 5 where the minimum temperature for *Cydia succedana* activity was 10 - 11.5°C.

The germination of fallen seed was similar, regardless of climatic conditions or site altitude. However, there were differences from month to month. This indicates that there are periods of the year when gorse seed is less viable. This was particularly so with the fallen seed at Bainham, where the autumn/winter fallen seed had a low germination rate of 10 – 30% (Fig. 6.1a).

The seed from pods sampled during the summer showed that, in Golden Bay, gorse seed viability was higher than seed produced further south. This, coupled with the prolonged seed production season makes Golden Bay an ideal production area for gorse seed. Over the summer the Golden Bay sites produced a high percentage of viable seed (approx. 80%). However, there was no significant difference among sites (Fig. 6.1b). The Golden Bay site seed from pod samples also has very high seed viability throughout the year (approximately 80%) over the whole experimental period (Fig. 6.1c).

The fallen seed caught in the seed trays had a lower germination rate than picked seed. This was contrary to previous work (e.g., Ivens, 1983). Ivens (1983) took gorse seed from the soil; collected seed from trays placed under gorse bushes and took seed from ripe pods. There was a higher proportion of hard seed in seed from pods than in seed collected from seed trays and very little of the seed from the soil was hard.

The seed from the trays and from the pods all had the same scarification treatment but the seed in Golden Bay, especially East Takaka, had a consistent percentage of 80% germination from the sampled pods. However, the percentage of germinated seeds from the seed fall trays was considerably lower (60%). At Hinewai and Trotters Gorge the highest percentage of viable seed was from the seed trays (approximately 50%).

Plate 6.1: Seed tray showing seeds caught.

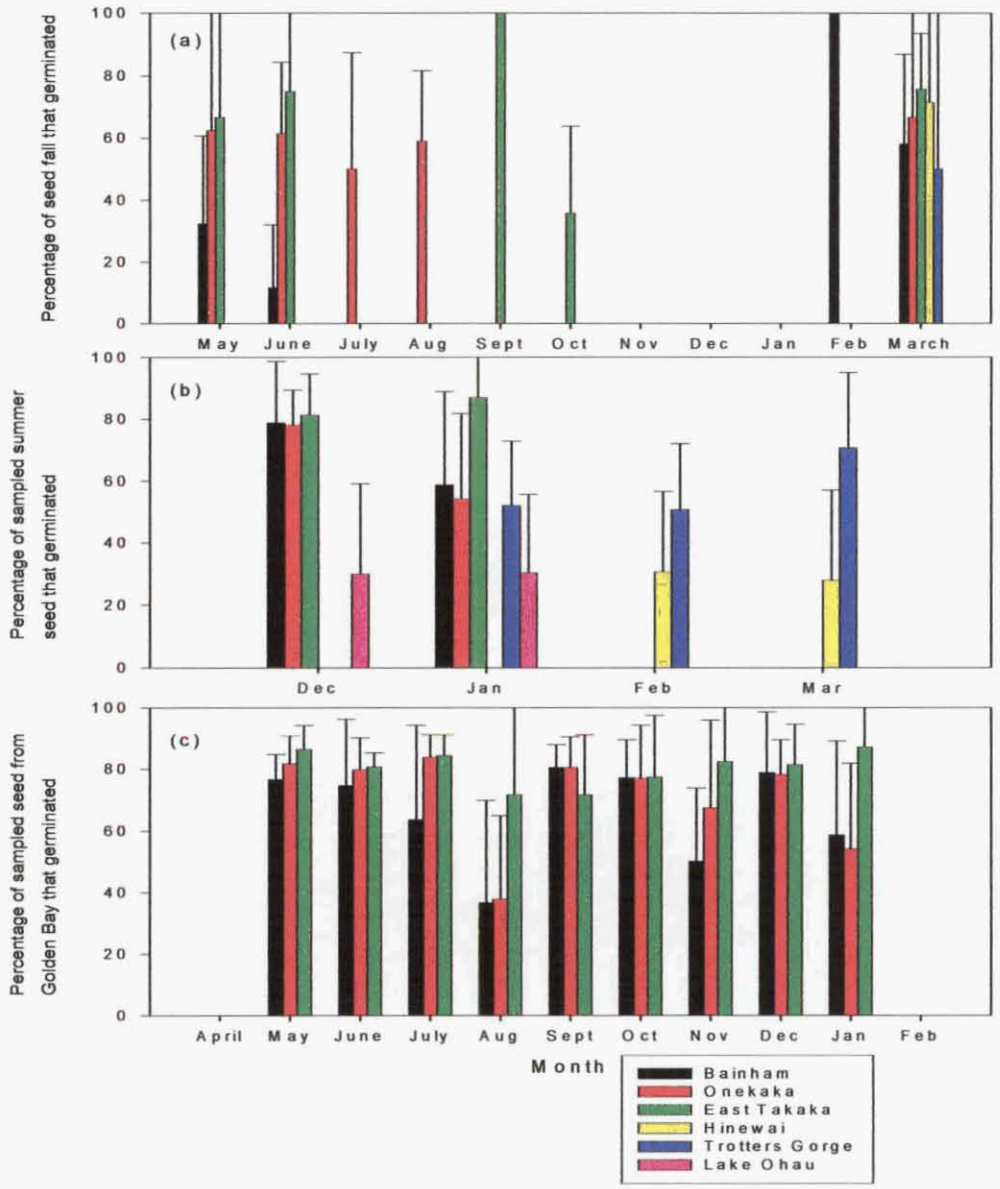


Figure 6.1. Monthly gorse seed germination (%); a) seeds that had fallen into seed trays; b) seed sampled from the six sites during spring-summer; c) seed sampled from Golden Bay sites over the total study. (There was no seed fall in trays at Lake Ohau). I = SE.

The pods bursting when the seeds were ripe may have resulted in the seeds being spread further a field than the seed tray. Most seed falls directly below the gorse plant, although seeds can be thrown up to 5 m from the parent plant by pod dehiscence (Moss, 1960). Also worth considering was the bush size. Many of the sample bushes (Golden Bay, Hinewai Reserve and Trotters Gorge) were over 3 m

and covered much ground. Gorse reproduction takes place in the leaf axils of the previous year's growth (Clements *et al.*, 2001) and so parts of the bushes that were producing seed may have been outside the direct fall to the seed trays. Also, some of the sample bushes were in areas grazed by livestock. Because of this, the seed trays were placed as close as possible to the trunk. This may have meant that when the pods burst and dispersed the seed, there was a reduced possibility of catching the falling seed. Further research should include the possibility of having seed trays set at various distances from the trunk centre.

Another factor in the observed reduction of seed falling into the seed trays may have been due to gorse seed biological control agents having an effect and reducing production of viable seed. The initial release of the gorse pod moth was in 1992 and it has now become established throughout New Zealand (Hayes, 1999).

6.5 Conclusions

The results of this experiment indicate that gorse seed that reaches maturity and falls to the ground has a viability of approximately 60%, whereas seed from pods sampled from the plant has a viability of approximately 80%. This was especially so in Golden Bay. Southern regions have only one reproductive cycle per year whereas Golden Bay has two. These southern regions also have lower seed viability. The fallen seed had a higher viability than the sampled pod seed in the southern regions, whereas the opposite was true for seed from Golden Bay.

The gorse bushes in Golden Bay, Trotters Gorge and Hinewai Reserve were over 3 m high. The bushes at Lake Ohau had an average height of 1.5 m. This factor as well as the harsh winter conditions means that much less seed was produced at Lake Ohau. The southern sites had only one reproductive cycle a year. This would be because during the winter months the average monthly minimum temperature was below 0°C or close to 0°C. Average monthly minimum temperatures in Golden Bay were not as low, so the bushes could produce seed uninhibited by low temperature.

CHAPTER 7

CONCLUSIONS

With regard to the objectives outlined in the Introduction (Chapter 1), the following conclusions can be drawn regarding *Cydia succedana* and the host plant, *Ulex europaeus.*

7.1 Conclusions

1. *Cydia succedana* eggs and larvae have a lower development threshold of approximately 11.5°C. The upper threshold was not determined. This was similar to expected results, as other members of the same genus have a lower threshold of approximately 10°C.

2. *Cydia succedana* larvae required 588 degree-days to develop from egg to moth. This was higher than other species of the same genus but further tests may reduce the value since this was based on a single measurement due to the difficulty in raising the larvae.

3. It was found that the survival rate of larvae at 25% was lower than earlier research work on species of the same genus, where the survival rate was 36%. Again, with repeated experiments, the percentage of *C. succedana* larvae that survive may be increased.

4. The number of larval instars suggested is six, similar to other members of the same genus. Again, due to difficulty in rearing larvae, this is based on limited data. For a definite count of larval instar more measurements are required.

5. Measuring of the number gorse pods damaged by *C. succedana* larvae saw two – three pods damaged. *Cydia nigricana* (pea moth), which is approximately the same size as *C. succedana,* damages all of the seed in a pea pod. Comparative measurements of the weight of pea and gorse seed were not made and it may be that *C. succedana* larvae are damaging the same

seed biomass as *C. nigricana*. In order to do this, it would be necessary to damage the seed in several pods. It was noted that gorse pods in Golden Bay had a higher number of seeds per pod (7 – 8) than pods from the southern sites (5).

6. The phenology of *C. succedana* showed that, at McLeans Island, there were two generations, in November 2002 and February 2003. At Hinewai, there was less evidence of a second generation, although it was present and *C. succedana* was later becoming active in the spring. There were considerably more male moths trapped throughout the year at McLeans Island, which was a warmer, drier area. McLeans Island moth phenology was synchronised with gorse phenology in the first generation, but there was less synchronicity for the second generation.

7. *Cydia succedana* has established itself in Golden Bay and is damaging a relatively high percentage of gorse seed. Further south there was not the same high level of *C. succedana* activity found in sampled pods but there was more evidence of activity by *Exapion ulicis*, especially at Lake Ohau.

8. The infestation of gorse pods by *E. ulicis* and *C. succedana* varied from site to site. There were considerably more *C. succedana* larvae active in the warmer area of Golden Bay than in the cooler areas of the Banks Peninsula, North Otago and Mackenzie Basin where *E. ulicis* was more plentiful.

9. Of the seed fall seed collected in trays, less was viable (60%) than seed from sampled pods on gorse plants (80%), which was contrary to the results of previous studies.

10. The Golden Bay pod sampled seed and the seed fall seed had a higher viability than seed from Canterbury and North Otago (80% v 50%). Lake Ohau seed had less viable seed (30%) and produced seed for a shorter period.

11. Gorse seed fall in this study was considerably less than previously reported. This may have been due to predation by the seed-feeding agents, or it may be

due to attacks by other seed-feeding organisms such as various fungi. In addition, previous studies have had four seed trays per sample, whereas this study only had one seed tray per sample. Further trials should include measuring seed fall at different distances from the trunk.

7.2 Evaluation against objectives

1st objective

The phenology of *C. succedana* for different parts of the South Island of New Zealand has been determined. Two sites, McLeans Island and Hinewai Reserve, were used to observe the phenology of *C. succedana.* It was found that *C. succedana* activity was affected by climatic conditions and the daytime temperature was the main factor. *Cydia succedana* did not begin being active at Hinewai Reserve in large numbers until November, whereas at McLeans Island, activity began in September.

The temperature also governs the phenology of the gorse plant, as was evident by differences in flowering and producing seed time, as well as amount of seed produced. At the other sites, the phenology of the gorse was noted and in the southern regions, where the daily temperature goes below zero, the gorse bushes only had one seed production season, and air temperature controlled the timing. The activity of *C. succedana* at the other sites was noted and *C. succedana* was more active at the warmer sites (Golden Bay) than at the southern sites.

2nd objective

The number of larval instars was ascertained for the small number of larvae that were collected. From the limited information obtained, the number of instars was calculated to be six. This is similar to other species of the same genus, but further research is required to confirm this.

3rd objective

Investigation of the infestation of gorse pods by *C. succedana* and *E. ulicis* was completed. Through this, it was apparent that *E. ulicis* has the dominant role in damaging gorse pods in the southern region, where the winter is colder and longer. In

Golden Bay, where there is a warmer climate, *C. succedana* damaged more gorse seed pods.

Measurement of the number of gorse seed pods attacked by *C. succedana* was completed to a limited degree. From the results, it appears that each *C. succedana* larvae damages 2 – 3 seed pods.

4th objective

Assessment of the viability of seed fall and pods sampled seed has been determined. The results were that the higher viability was the sampled pod seeds. This was contrary to previously published results.

Seed fall counts were completed at each site. The results were variable. The highest number of seeds collected was considerably lower than previous research work. This may have been caused by the presence of seed feeding agents, which had not been established in New Zealand at the time of the previous work. In addition, the sampling method may have not trapped all seed falling from any sample gorse bush.

7.3 Future research

Further research in this field should include more work in the determination of the number of larval instars. This would help to determine more accurately how many instars are present. In addition, more research in the temperature threshold field would assist in the determination of the lower and upper thresholds.

Having more larvae with which to test the number of pods attacked would allow more accurate calculations to be made on the number of pods that would be damaged. This would then ascertain whether the release of further seed feeders would be necessary to gain greater control of gorse seed production.

Future work on the effectiveness of *C. succedana* for gorse control should also include tests on the likelihood of seed pods of other legumes being attacked. Computer modelling would be of assistance for assessing the likelihood of *C. succedana* causing damage to native flora. More work should also be conducted on the amount of *E. ulicis* larvae that are eaten by *C. succedana* larvae.

Further investigation into the annual seed fall would be useful, as it would assist in making decisions on whether more seed-feeding insects would be

complementary towards the biological control of gorse in New Zealand. If at all possible, the future research should place seed trays at different distances from the trunk.

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Appendix 1 Individual sample GPS and altitude
Appendix 2 Daily records of rainfall (mm)
Appendix 3 Daily minimum and maximum temperatures (°C)
Appendix 4 No of seeds produced and seed viability; seed fall and viability of seed fall.
Appendix 5 The effect of temperature and scarification method on gorse seed germination.
Appendix 6 Impact of *Exapion ulicis* (Forster) (Coleoptera: Apionidae) on gorse seed viability.
Appendix 7 5% LSD difference between McLeans Island and Hinewai Reserve pheromone traps
Appendix 8 Male moth numbers caught in pheromone traps
Appendix 9 Plant activity (estimated % of reproductive activity)
Appendix 10 Percentage of pods damaged by *Exapion ulicis* and *Cydia succedana*
Appendix 11 Estimates of gorse bush heights (mm)